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CALIBRATION OF THE AEDC-PWT 4-FT TRANSONIC TUNNEL WITH MODIFIED WALLS

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J. L. Jacocks and M. S. Hartley

ARO, Inc.

June 1969

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*Now with Westinghouse Electric Corporation, West Mifflin, Pennsylvania

FOREWORD

The work reported herein was sponsored by Headquarters, Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), Arnold Air Force Station, Tennessee, under Program Element 65401F.

The results of research presented were obtained by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of AEDC, AFSC, under contract F40600-69-C-0001. The research was conducted from January 21 to January 24, 1969, under ARO Project No. PC0937-C80, and the manuscript was submitted for publication on May 20, 1969.

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This technical report has been reviewed and is approved.

Richard W. Bradley Lt Colonel, USAF AF Representative, PWT Directorate of Test	Roy R. Croy, Jr. Colonel, USAF Director of Test

ABSTRACT

Tests were conducted in the AEDC Aerodynamic Wind Tunnel, Transonic (4T), to determine the tunnel calibration and centerline Mach number distributions. The wall porosity in the test section is remotely variable using a sliding cutoff plate design. The walls were recently modified to allow upstream movement of these cutoff plates instead of the original downstream movement for decreasing porosity. During the tests, Mach number was varied from 0.10 to 1.35, test section wall angle from -0.5 to 0.5 deg, test section wall porosity from 0- to 10-percent open area, and stagnation pressure from 1000 to 3500 psfa. Some data were obtained showing the effects of humidity. Acceptably uniform Mach number distributions were obtained at wall porosities up to 7-percent open area, a marked improvement over the original 4T wall design. The tunnel plenum-stream calibration relationship was determined to be dependent upon Mach number, wall angle, wall porosity, and humidity but nominally independent of stagnation pressure level.

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I. ILLUSTRATIONS

NOMENCLATURE

a, b	Surface fit constants
M	Mach number
M_c	Equivalent plenum Mach number
M_1	Average free-stream Mach number
p_c	Plenum pressure, psfa
p_e	Diffuser exit pressure, psfa
p_t	Stagnation pressure, psfa
x	Tunnel station, in.
θ_w	Test section wall angle, deg (positive diverged)
λ	Tunnel pressure ratio, p_t/p_e
σ	Standard deviation

τ	Wall porosity, percent
ω	Specific humidity, lb water/lb dry air

SECTION I
INTRODUCTION

The PWT Aerodynamic Wind Tunnel, Transonic (4T), began operation in December 1967. The initial calibration of the variable porosity wall test section was conducted intermittently from December 1967 to February 1968 and is reported in Ref. 1.

During the initial calibration, an overexpansion at supersonic Mach numbers occurred in the tapered porosity region. While it was possible to control the over-expansion by modifying the tapered porosity section, the wave cancellation properties of the walls were not up to expectations.

A study was initiated in the PWT Aerodynamic Wind Tunnel, Transonic (1T), to establish the corrective measures necessary. The results of that study (Ref. 2) indicated that by reversing the direction of the cutoff plate motion, very good wave cancellation properties were obtained. Acceptable Mach number distributions were also obtained with the scaled original 4T tapered porosity region as evidenced in Ref. 3.

The 4T test section walls were then modified to allow upstream cutoff plate motion for decreasing porosity as opposed to the original downstream motion. The results of the test section Mach number calibration of 4T with the modified walls are included in this report, superseding the Ref. 1 results.

SECTION II
APPARATUS

2.1 BASIC TUNNEL

Tunnel 4T is a closed-loop, continuous flow tunnel with a usable Mach number range from 0.10 to approximately 1.35. It is a variable density tunnel with a stagnation pressure range from 300 to 3700 psfa. Presently, only limited control of stagnation temperature is possible in the range of approximately 80 to 110°F.

The test section flow is generated through a two-dimensional, fixed, sonic-block nozzle with parallel sidewalls. Supersonic speeds are obtained by expansion through the upstream 3 ft of the test section. The top and bottom test section walls may be converged or diverged 0.5 deg.

The model support systems located in the diffuser section consist of a half-sector sting support with an angle-of-attack range from 28 to -12 deg with the pitch center located at station 108 and a six-degree-of-freedom store support for store separation or small model testing. The latter is controlled by a digital computer, and a store trajectory may be determined either by a point prediction method or by data from a preselected grid pattern. Movable sidewalls in the diffuser region alleviate blockage of the model support systems. Access to the model for minor changes is provided by moving one of the diffuser sidewalls to its extreme position.

Tunnel 4T is normally powered by the second increment of the 178,000-hp PWT Plenum Evacuation System (PES). The PES consists of two increments which may be operated independently, thus making it possible to run 4T simultaneously with either of the PWT 16-ft tunnels.

The location of 4T in the PWT complex is shown in Fig. 1, Appendix I, and the general arrangement of 4T is given in Fig. 2. Additional information on 4T and the PES is available in Ref. 4.

2.2 CALIBRATION EQUIPMENT

A centerline static pipe was used to determine Mach number distributions. The pipe is supported at its downstream end by the half-sector model support and at its upstream end by forward swept support struts attached to the nozzle sidewalls. An 11,000-lb tension preload was applied to the pipe with spring washers at the forward support struts. A sketch of the pipe installation is given in Fig. 3.

2.3 TEST SECTION WALL GEOMETRY

The airside test section wall geometry is sketched in Fig. 4. The maximum wall porosity of 10 percent is defined as the area of a hole based upon the diameter divided by the area of the parallelogram formed by a four-hole pattern.

The variable porosity feature is obtained utilizing a sliding cutoff plate behind the airside plate with identical geometry. The combined plate geometries of the original 4T design and of the modified walls with upstream cutoff plate motion are sketched in Fig. 5.

SECTION III
PROCEDURE

3.1 TEST PROCEDURE

The primary variables during the Mach number calibration were wall porosity, wall angle, pressure ratio, and plenum suction. A series of wall statics manifolded to read an average value provided an approximate indication of the test section Mach number. This Mach number was set by varying plenum suction (supersonic) and/or main-stream pressure ratio (subsonic). In subsonic flow, the pressure ratio was adjusted until uniform distributions were obtained at the downstream end of the test section. For supersonic Mach numbers, the pressure ratio was usually fixed at approximately $\lambda = 1.4$. Throughout most of the calibration, a wall porosity was set; and data were taken through the Mach number range, varying wall angle at each Mach number.

A stagnation pressure of approximately one atmosphere was maintained for the majority of the data. Special runs of varying pressure levels were made to check the Reynolds number effect on the results. The stagnation temperature varied from 80 to 110°F. All pressures were measured using the standard tunnel pressure system and 5-psid self-balancing transducers referenced to plenum pressure.

3.2 DATA REDUCTION

Mach number distribution data were obtained on-line using the PWT digital computer and data acquisition system. Local Mach numbers were calculated from the static pressure measurements and tabulated using a line printer. The data were also displayed on a cathode ray tube plotter as a function of tunnel station. The average Mach number and the 2-σ deviation were calculated for the values downstream of station 72. The ratio of plenum pressure to stagnation pressure was used to calculate an equivalent plenum Mach number.

The equivalent plenum Mach number is used as a means of setting test section Mach number during normal testing; therefore, it was necessary to develop a relationship between this parameter and other tunnel operating parameters. The parameters used are test section wall porosity and wall angle in addition to the plenum Mach number. The relationship developed is a hypersurface fit of the form:

$$M_1 = M_C - f_1(M_C, \tau) + f_2(M_C, \tau, \theta_W)$$

where,

$$\begin{aligned} f_1(M_C, \tau) = {} & a_1 M_C + a_2 \tau + a_3 M_C^2 \\ & - a_4 M_C \tau + a_5 \tau^2 + a_6 M_C^3 \\ & + a_7 M_C^2 \tau + a_8 M_C \tau^2 + a_9 \tau^3 + a_{10} M_C^4 \\ & - a_{11} M_C^3 \tau + a_{12} M_C^2 \tau^2 + a_{13} M_C \tau^3 \\ & - a_{14} \tau^4 + a_{15} M_C^5 + a_{16} M_C^4 \tau + a_{17} M_C^3 \tau^2 \\ & + a_{18} M_C^2 \tau^3 + a_{19} M_C \tau^4 + a_{20} \tau^5 + a_{21} \end{aligned}$$

and,

$$\begin{aligned} f_2(M_C, \tau, \theta_W) = {} & b_1 + b_2 M_C + b_3 \tau + b_4 \theta_W \\ & + b_5 M_C^2 + b_6 M_C \tau + b_7 M_C \theta_W \\ & + b_8 \tau^2 + b_9 \tau \theta_W + b_{10} \theta_W^2 \\ & + b_{11} M_C^3 + b_{12} M_C^2 \tau + b_{13} M_C^2 \theta_W \\ & + b_{14} M_C \tau^2 + b_{15} M_C \tau \theta_W + b_{16} M_C \theta_W^2 \\ & + b_{17} \tau^3 - b_{18} \tau^2 \theta_W + b_{19} \tau \theta_W^2 + b_{20} \theta_W^3 \end{aligned}$$

This surface fit was determined off-line.

3.3 ACCURACY OF THE RESULTS

Based on a confidence level of 95 percent, estimates of the errors in the data resulting from instrumentation errors are as follows:

ΔM	±0.002
$\Delta \tau$	±0.02
$\Delta \theta_W$	±0.03
$\Delta \lambda$	±0.001
$\Delta (p_c/p_t)$	±0.001

This Mach number error does not include the deviation from the average along the centerline or the inaccuracy of the surface fit which is discussed in Section 4.2.

SECTION IV
RESULTS AND DISCUSSION

4.1 CENTERLINE MACH NUMBER DISTRIBUTIONS

Comparisons of the original Tunnel 4T (Ref. 1) Mach number distributions obtained prior to the flow expansion region modification with representative distributions obtained with the present walls are presented in Fig. 6. For all supersonic Mach numbers significant improvement was obtained with the upstream cutoff plate motion. Of course, the full-open position (τ = 10) is the same geometry for both cutoff motions, and no change was noted at this porosity setting.

Mach number distributions obtained at 0-deg wall angle are presented in Fig. 7. The tunnel pressure ratios shown in Figs. 7a through 7c are not necessarily the optimum settings, as evidenced by slight gradients at the rear of the test section. For supersonic Mach numbers, the tunnel pressure ratio was held nominally constant at $\lambda = 1.4$. Since publication of Ref. 1, a vortex generator ring has been installed in the diffuser to prevent flow separation. Consequently, the required tunnel pressure ratios are slightly less than those shown in Ref. 1.

The distributions obtained with wall porosities above τ = 7 are generally not acceptable because of an uncontrolled overexpansion at the beginning of the the test section. It is, therefore, recommended that the maximum porosity be limited to τ = 7 for normal tests.

The influence of test section wall angle on the centerline Mach number distributions at τ = 3 is shown in Figs. 8a through 8c. These distributions are representative of data obtained at other wall porosities. For subsonic Mach numbers, the required tunnel pressure ratio increases with diverging wall angle. This sensitivity of pressure ratio to wall angle did not exist with the original wall/diffuser geometry. However, the original walls did show an interaction between tunnel pressure ratio and wall porosity, whereas the present wall configuration results in the required pressure ratio being essentially independent of wall porosity. Except for local disturbances at the beginning of the test section, wall angle variation has little effect upon the Mach number distribution.

A useful measure of the degree of flow uniformity is obtainable utilizing the standard deviation statistic, 2 σ. The variation of this parameter with free-stream Mach number is shown in Fig. 9. References to Mach number nonuniformity in Tunnel 4T should be stated in the form, $M_1 \pm 2\sigma$. These nonuniformities are less than ±0.005 from M = 0.10 to 1.05, ±0.01 at M = 1.20, and ±0.02 at M = 1.35.

The Mach number distributions are insensitive to tunnel stagnation pressure level, as shown in Fig. 10. Also indicated in the figure are the corresponding equivalent plenum Mach numbers, which show that the plenum-stream calibration relationship is independent of stagnation pressure.

Water vapor condensation was found to have a noticeable effect on both the centerline Mach number distributions and the plenum-stream calibration, as indicated in Fig. 11. With a relatively high humidity and visible condensation, the Mach number distribution is a function of humidity, but the plenum-stream calibration is nominally unaffected. At intermediate humidity levels (ω = 0.0017 for this test condition), the water vapor apparently condenses in the test section proper; and both the distribution and the plenum-stream calibration are variable with time resulting in an unacceptable test environment. This critical humidity level corresponds to a dew point temperature 3 to 4 deg below the dew point temperature at the onset of visible fog at p_t = 2000 psfa. Below this critical humidity level, both the distribution and the plenum-stream calibration are independent of humidity.

4.2 PLENUM-STREAM MACH NUMBER CALIBRATION

For perforated wall wind tunnels, it is generally accepted that the relationship between plenum pressure and free-stream pressure is independent of model size or shape. This assumption allows the setting and determination of free-stream Mach number from measurements of the tunnel stagnation and plenum pressures.

The plenum-stream calibration data and analytic approximation are shown in Fig. 12. In general, the approximation fits the data within the apparent repeatability band; however, errors as large as $\Delta M = \pm 0.01$ exist at the extreme wall angles.

For normal testing, it is recommended that the wall angle be fixed at $\theta_w = 0$. This results in a Mach number error attributed to the analytic approximation of less than ±0.002 throughout the wall porosity range. Inclusion of the tunnel instrumentation errors results in an overall Mach number setting error of less than ±0.003.

SECTION V
CONCLUSIONS

Based on the results from this calibration of Tunnel 4T, the following conclusions have been reached:

1. The Mach number distribution nonuniformities are less than ±0.005 from M = 0.10 to 1.05, ±0.01 at M = 1.20, and ±0.02 at M = 1.35.

2. Upstream cutoff plate motion provides a test section boundary far superior to that with downstream motion with respect to uniformity of the centerline Mach number distributions above M = 1.0.

3. Centerline Mach number uniformity and level is independent of tunnel stagnation pressure level for a fixed ratio of plenum pressure to stagnation pressure.

4. To ensure valid data, it is recommended that the tunnel dew point temperature be maintained at least 5°F below that corresponding to the visible water condensation point.

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2. Jacocks, J.L. "Reduction of Wall-Interference Effects in the AEDC-PWT 1-FT Transonic Tunnel with Variable Perforated Walls." AEDC-TR-69-86, May 1969.

3. Jackson, F.M. "Calibration of the AEDC-PWT 1-FT Transonic Tunnel with Variable Porosity Test Section Walls." AEDC-TR-69-114, to be published.

4. Test Facilities Handbook (Seventh Edition), "Propulsion Wind Tunnel Facility, Vol. 5", Arnold Engineering Development Center, July 1968.

APPENDIXES
I. ILLUSTRATIONS
II. TABLE

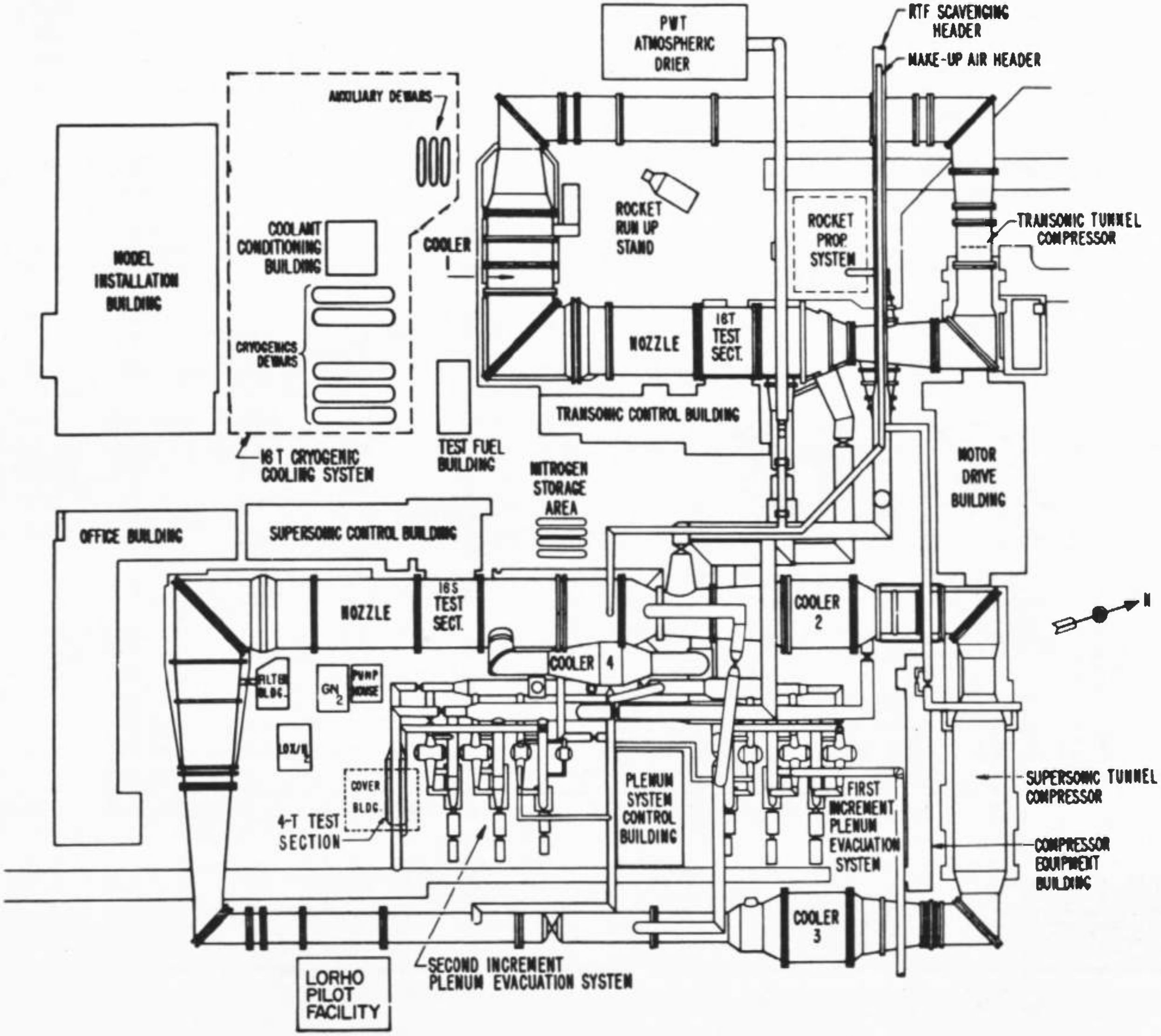


Fig. 1 Propulsion Wind Tunnel

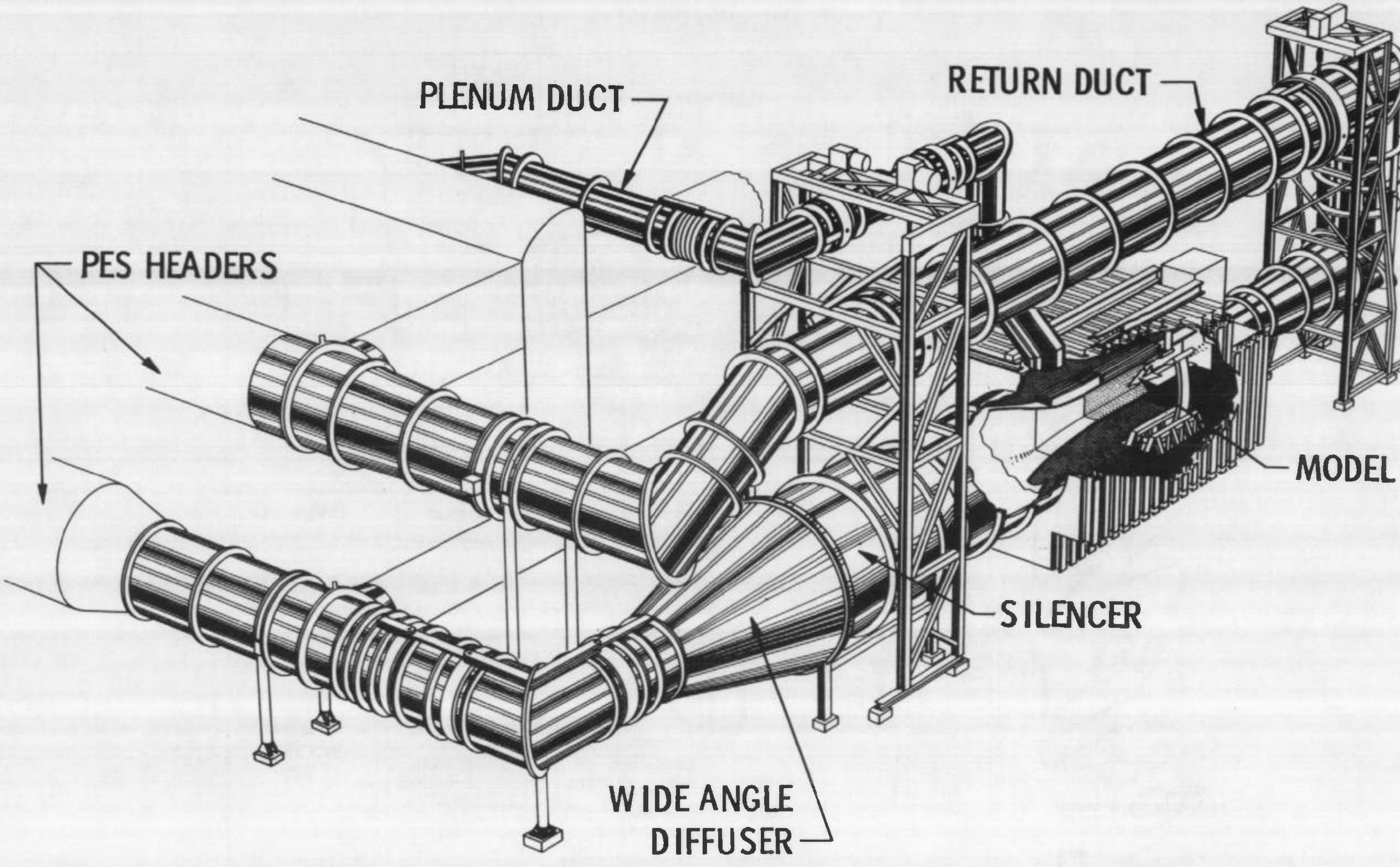


Fig. 2 Tunnel 4T General Arrangement

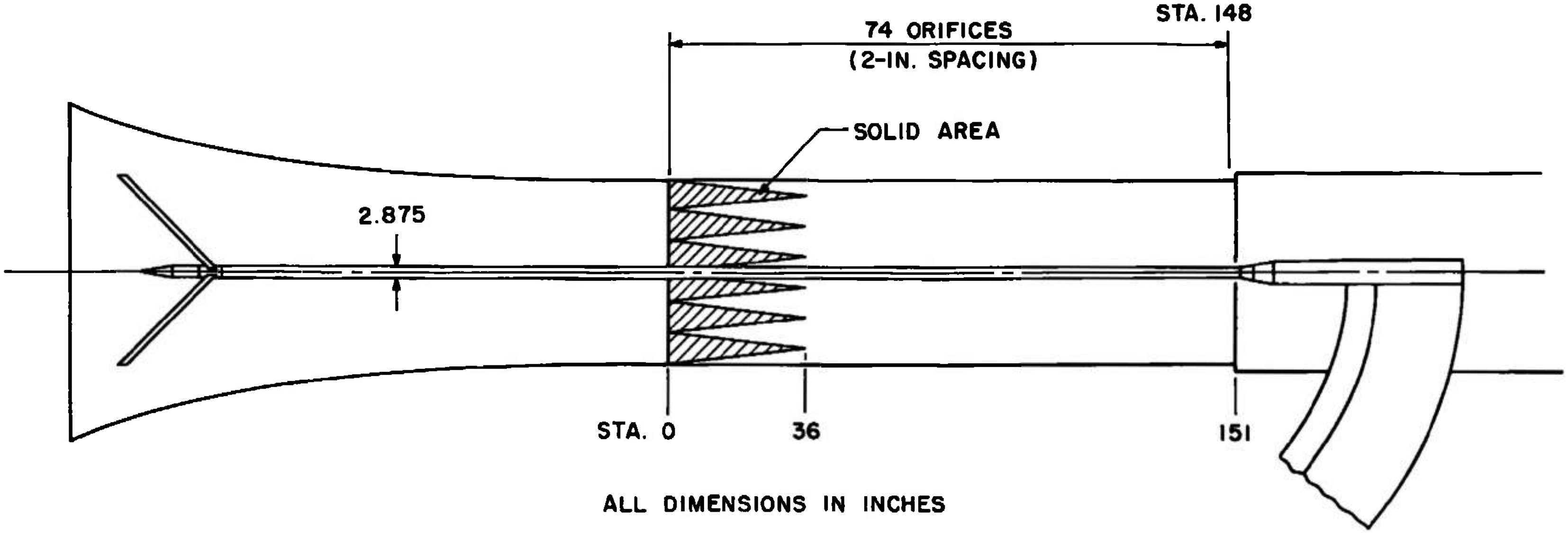


Fig. 3 Centerline Static Pipe Installation

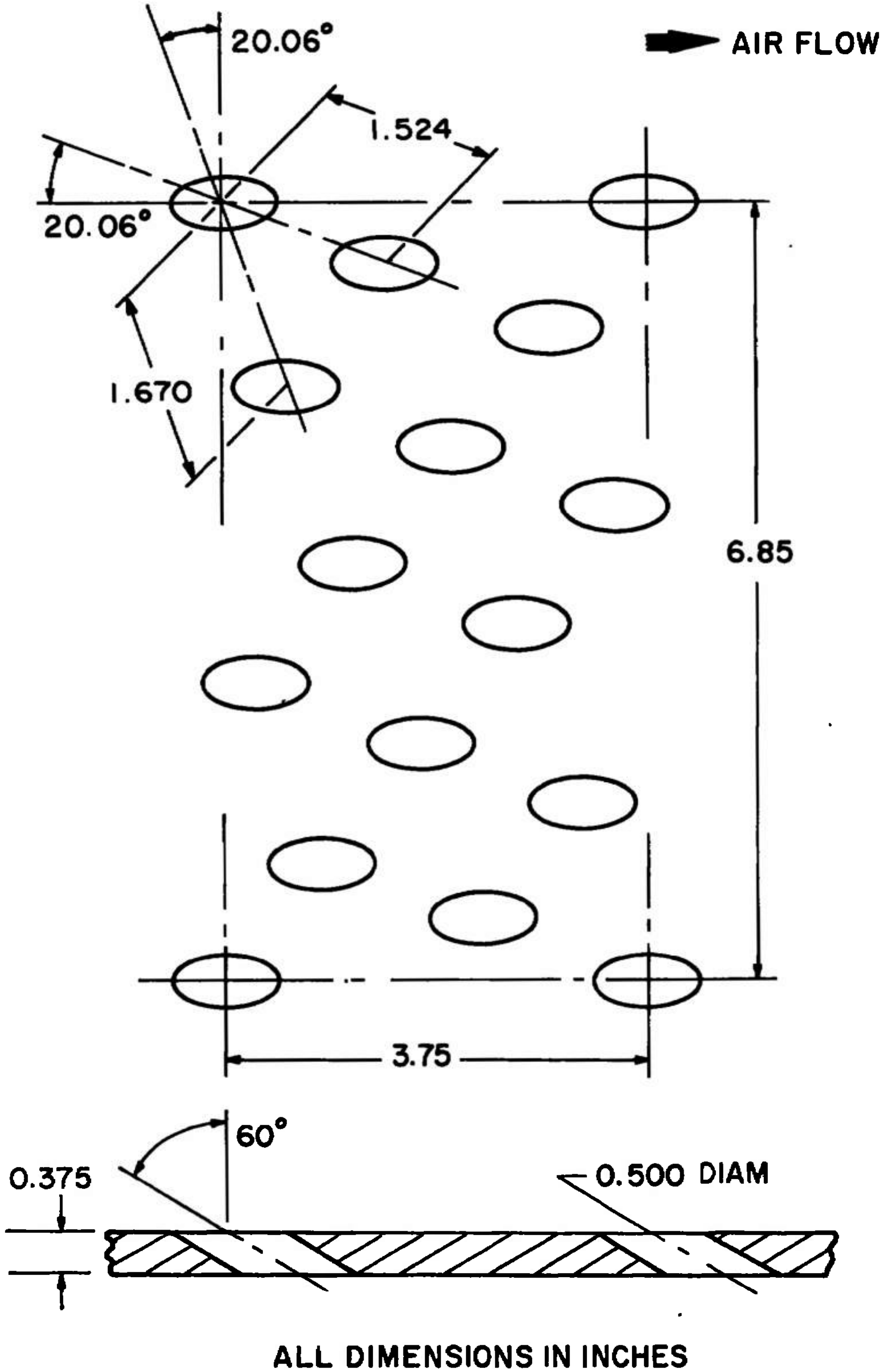


Fig. 4 Airside Test Section Wall Geometry

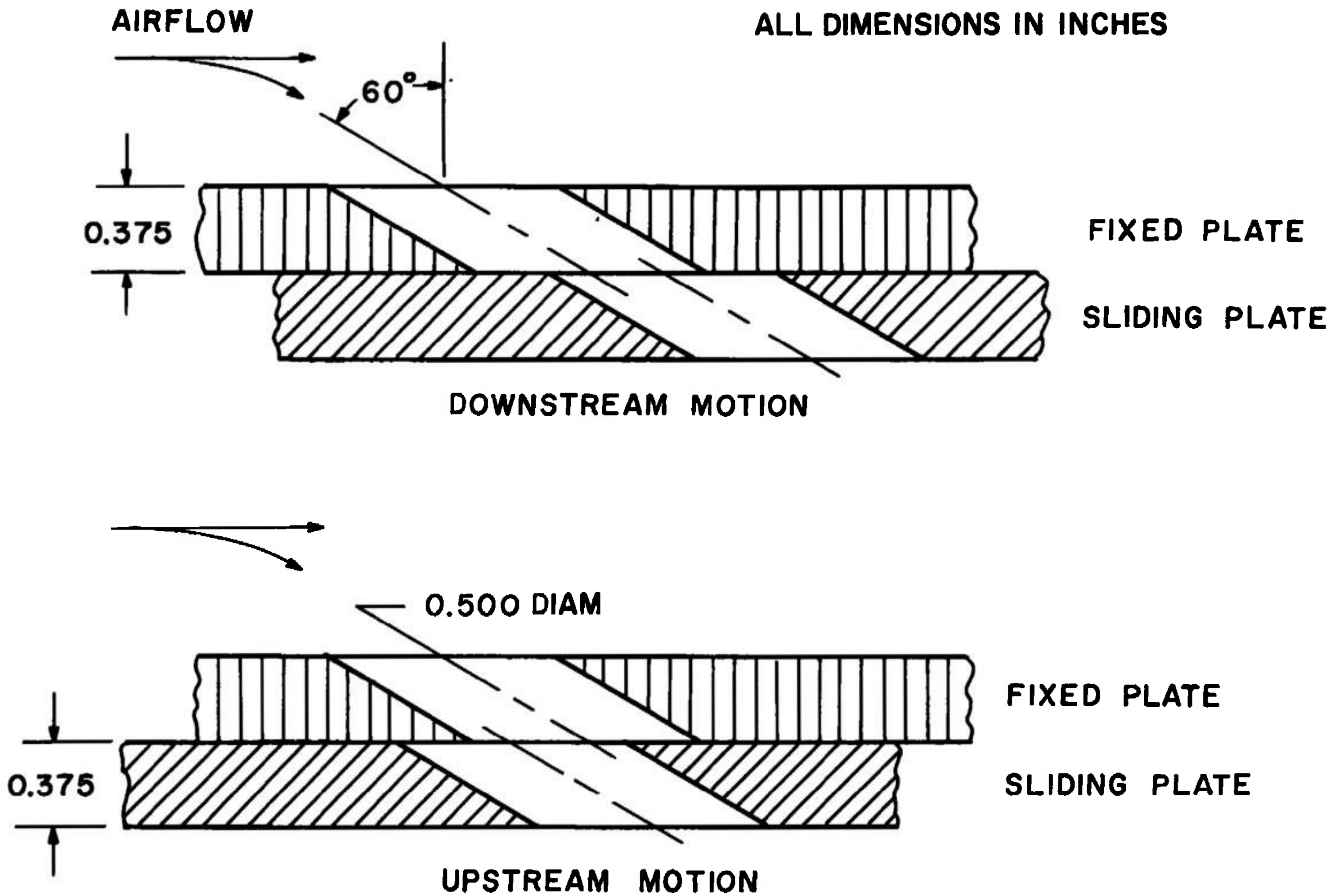
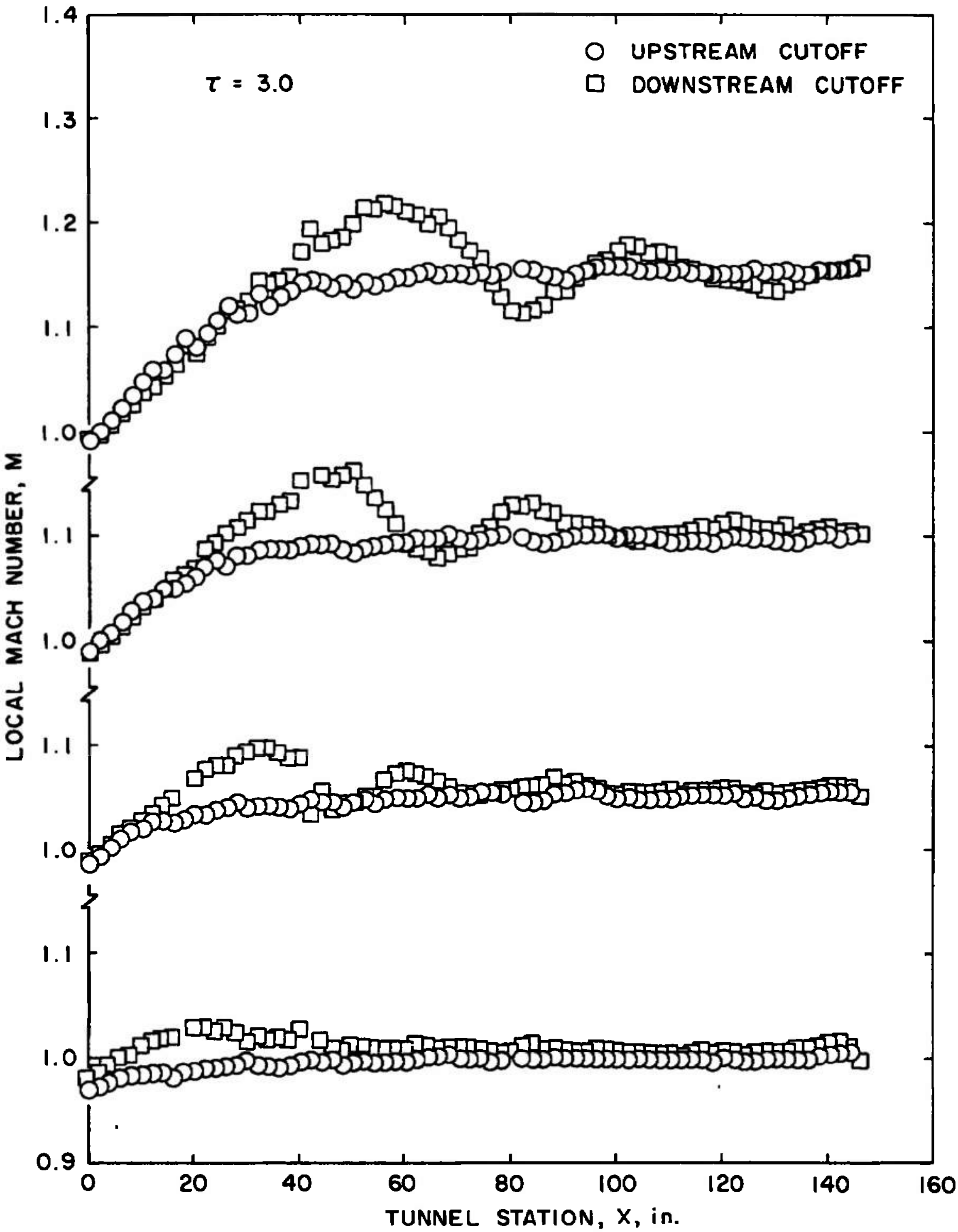
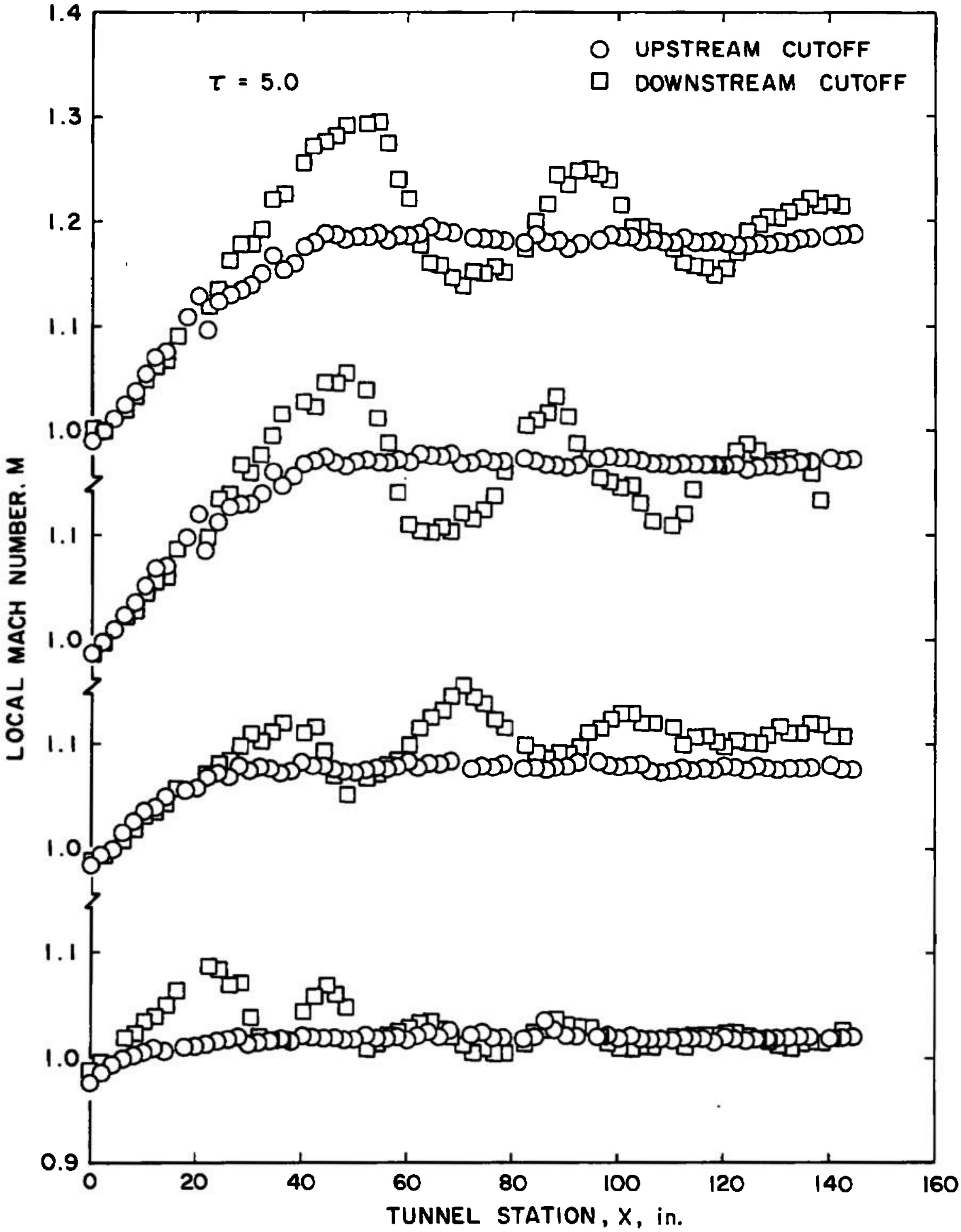


Fig. 5 Original and Modified Cutoff Plate Movement Geometry

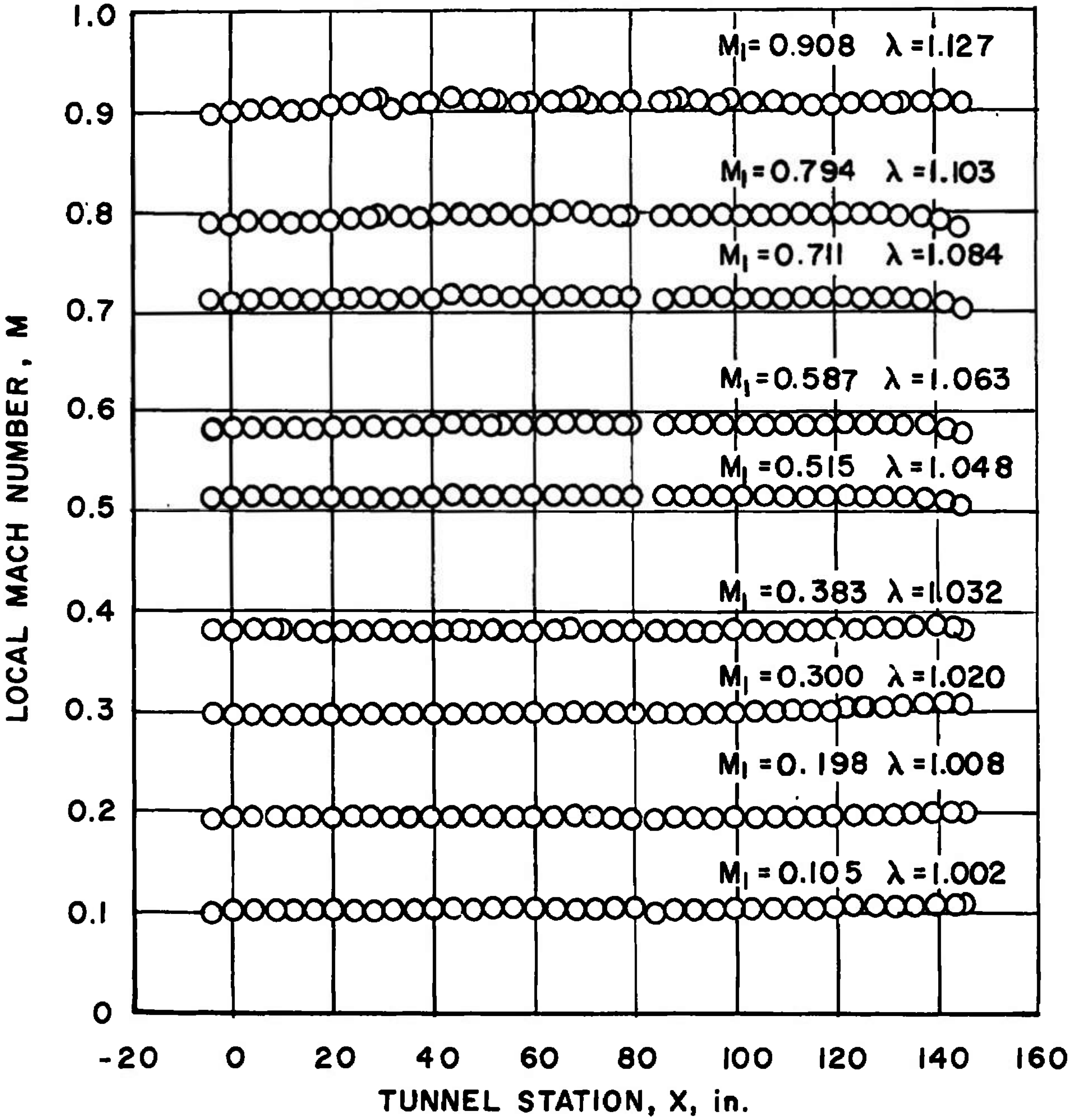


a. $\tau = 3.0$

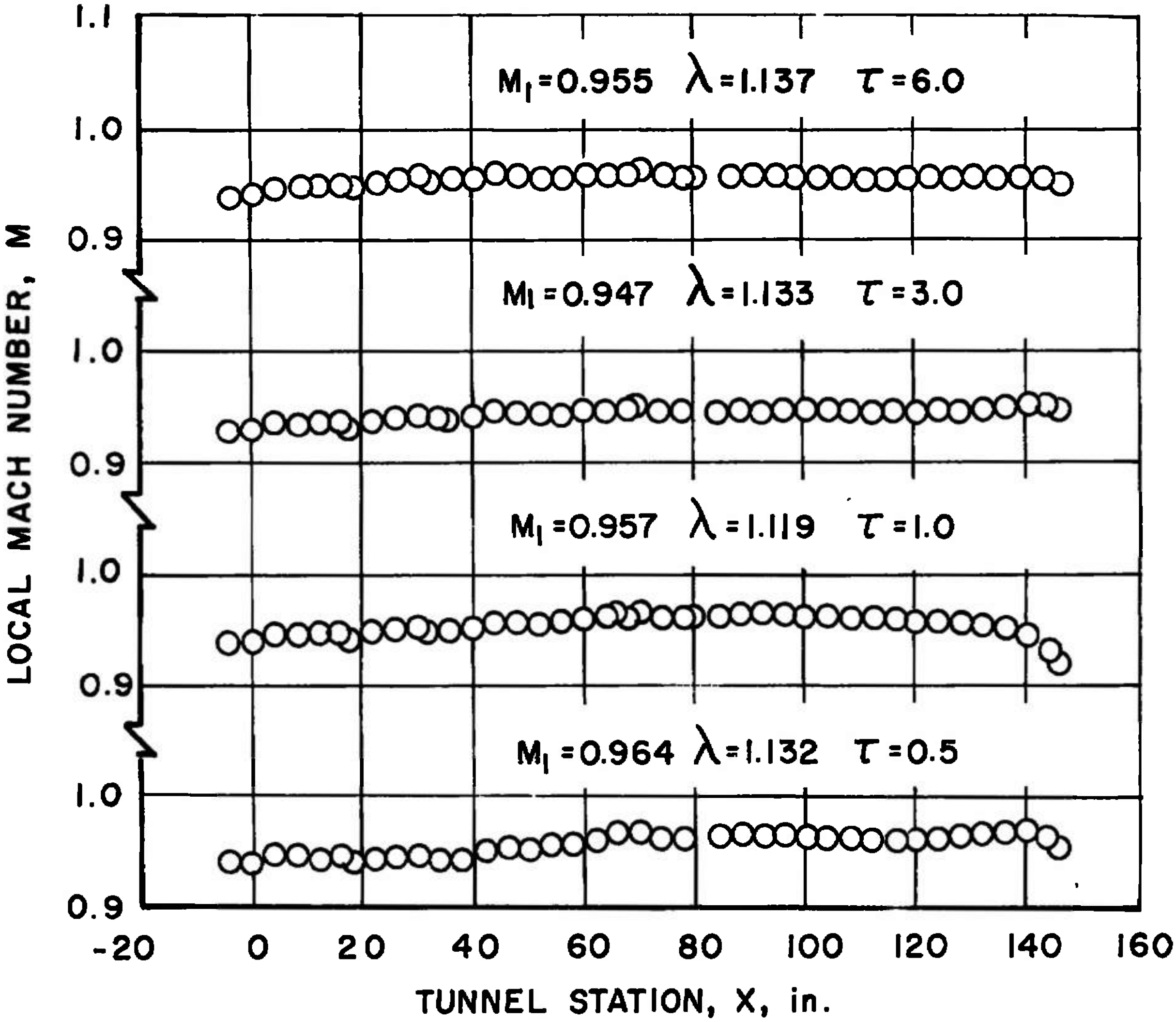
Fig. 6 Comparison of the Mach Number Distributions with Downstream and Upstream Cutoff Plate Movements, $\theta_w = 0$



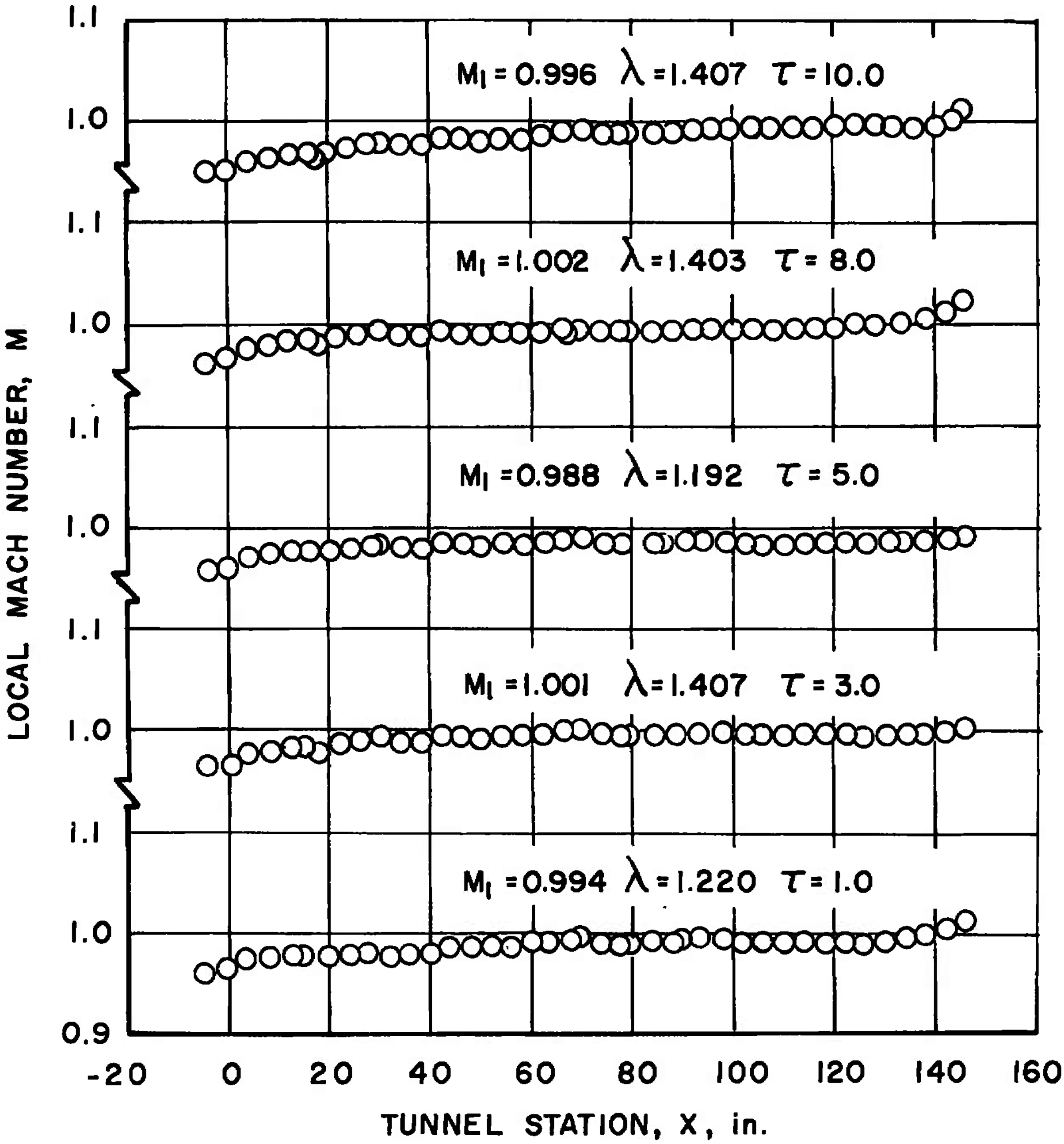
b. $\tau = 5.0$
Fig. 6 Concluded



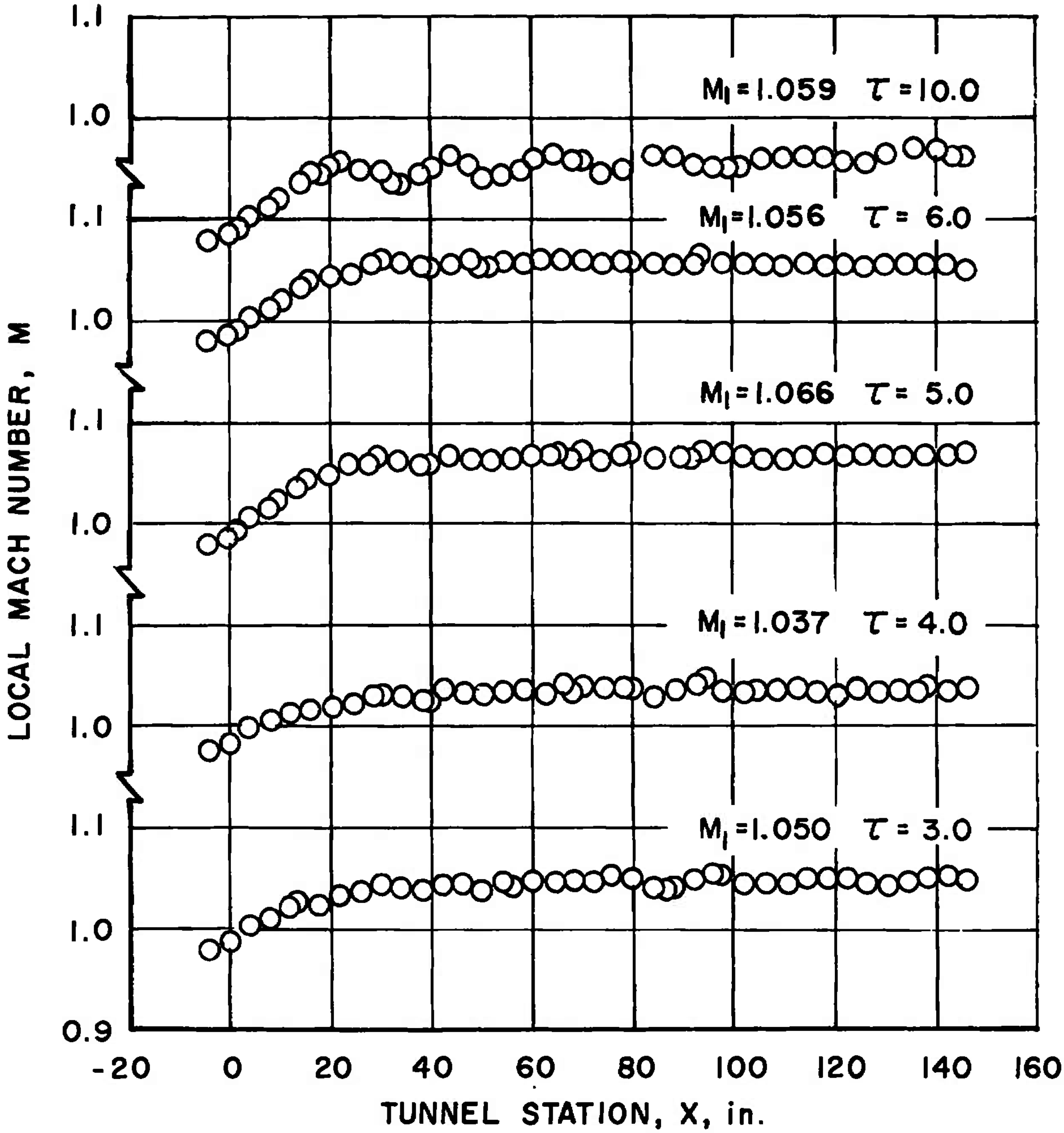
a. M = 0.10 through 0.90
Fig. 7 Centerline Mach Number Distributions, θ_w = 0



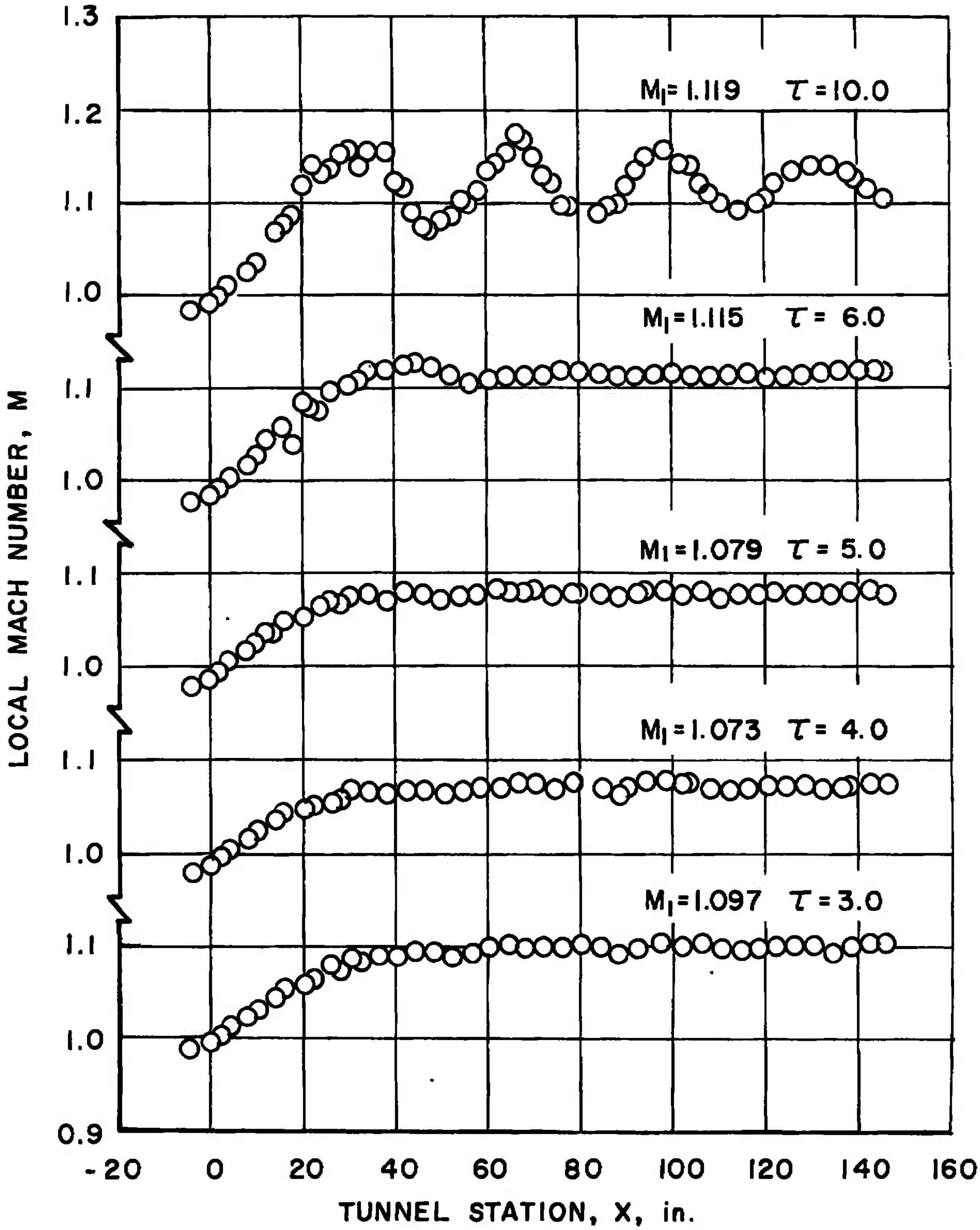
b. M = 0.95
Fig. 7 Continued



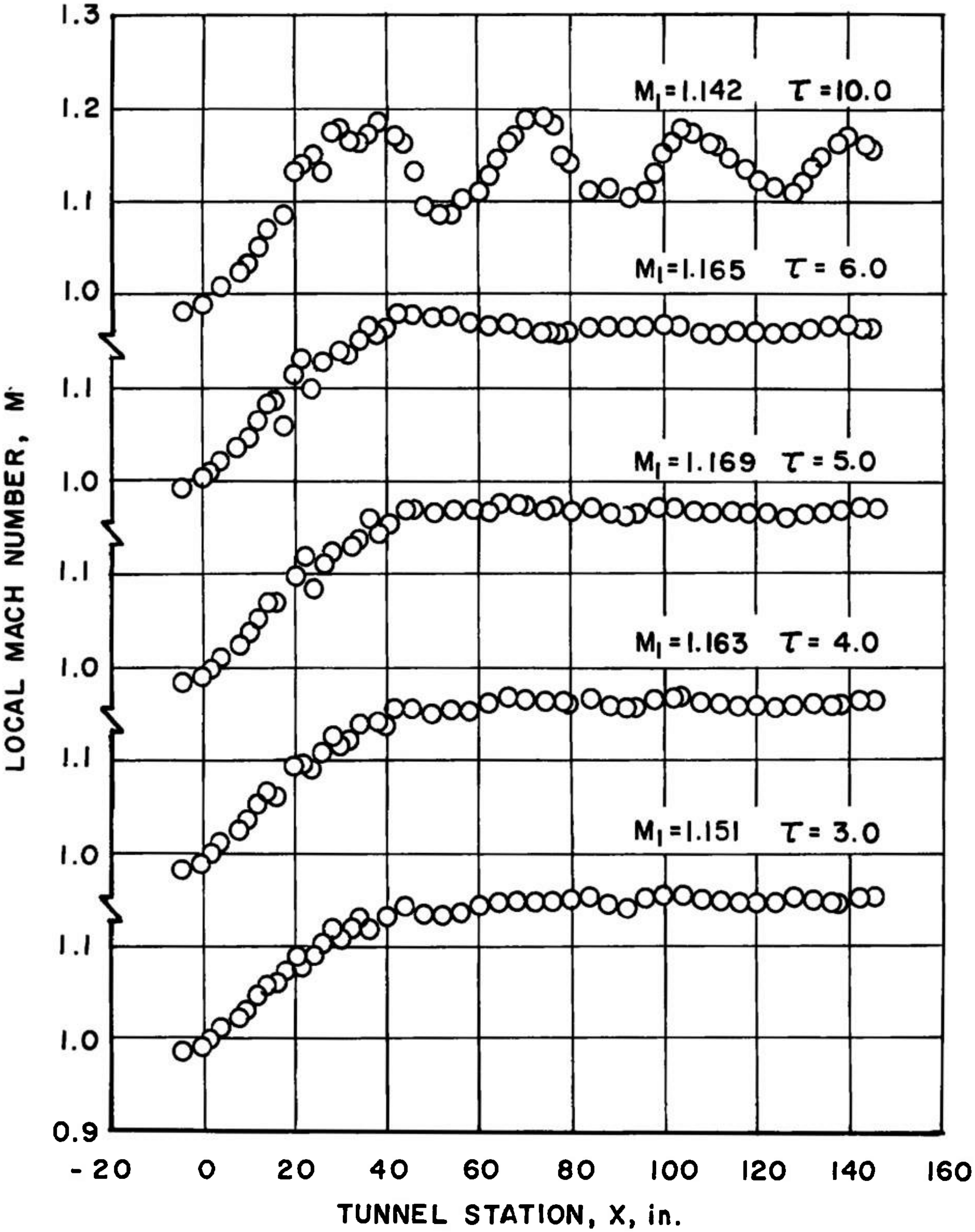
c. M = 1.00
Fig. 7 Continued



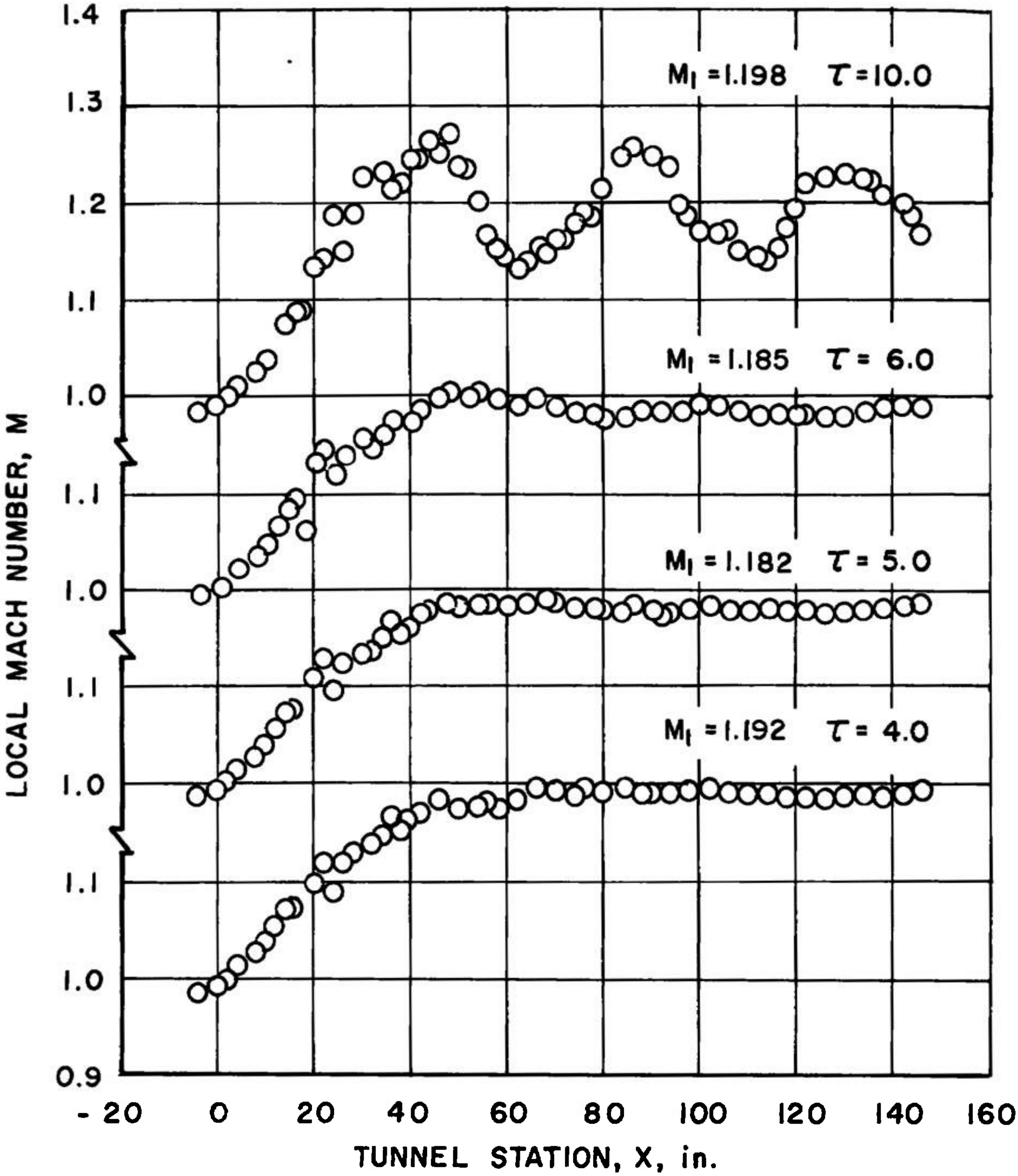
d. M = 1.05
Fig. 7 Continued



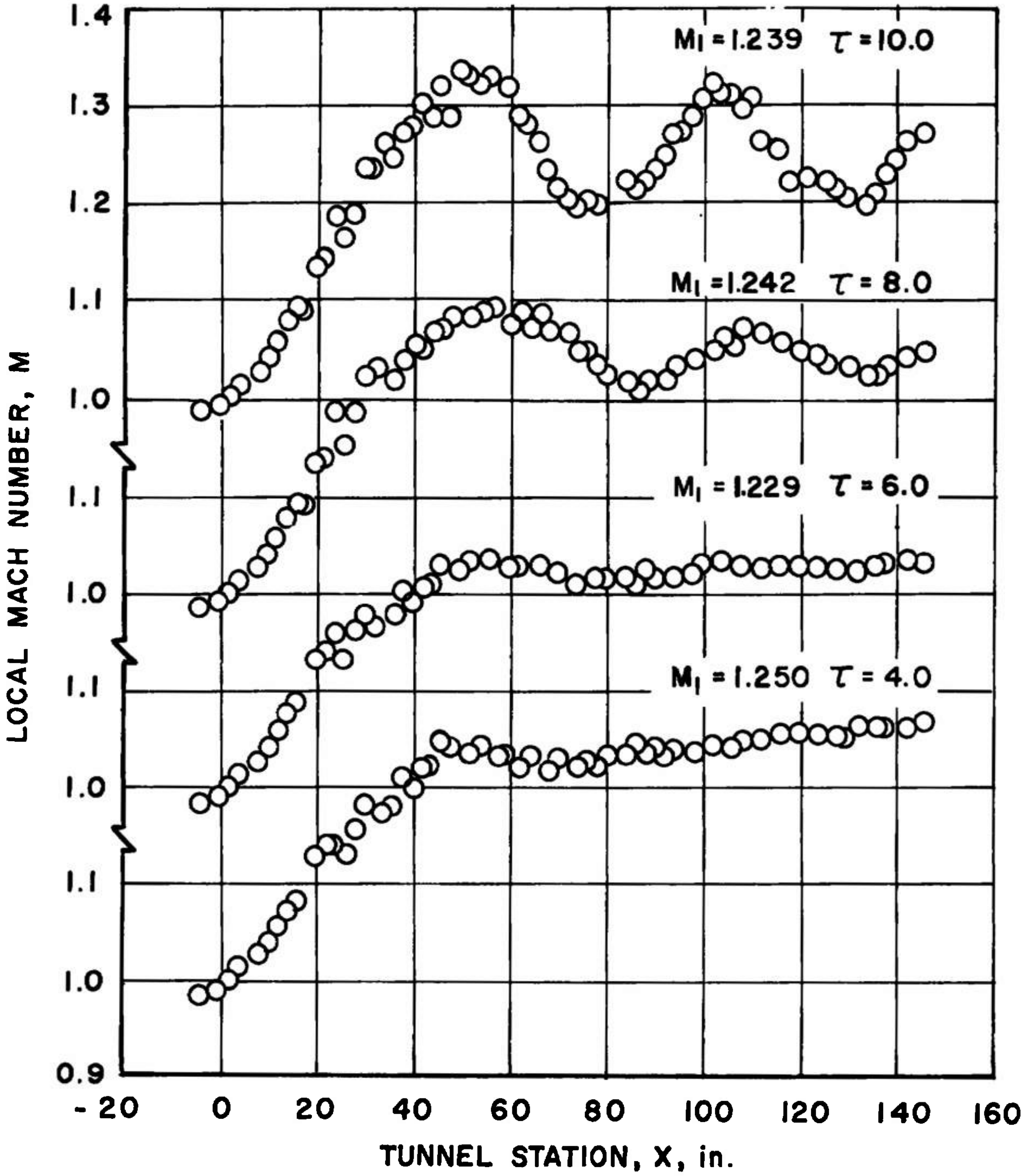
e. M = 1.10
Fig. 7 Continued



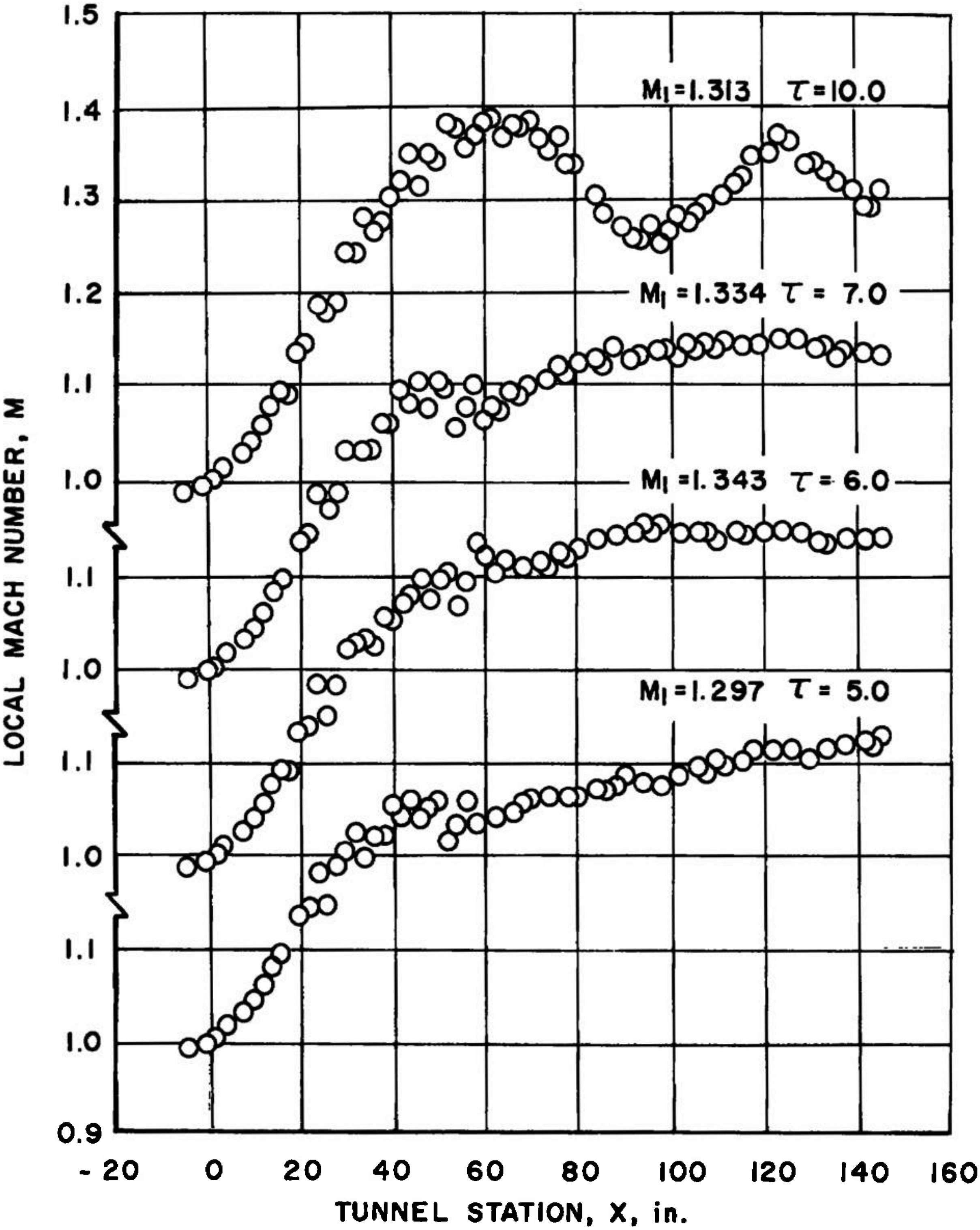
f. M = 1.15
Fig. 7 Continued



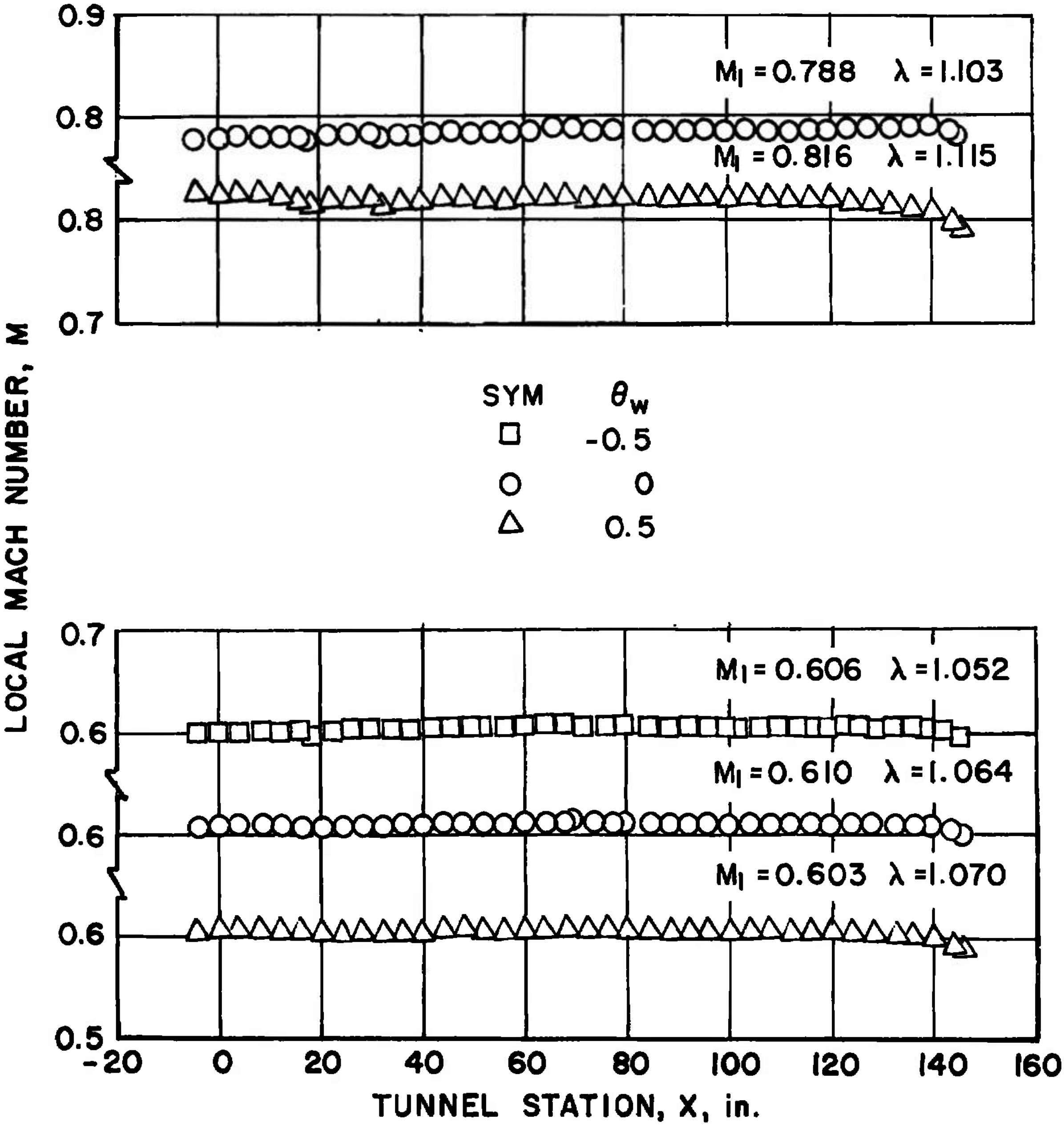
g. M = 1.20
Fig. 7 Continued



h. M = 1.25
Fig. 7 Continued

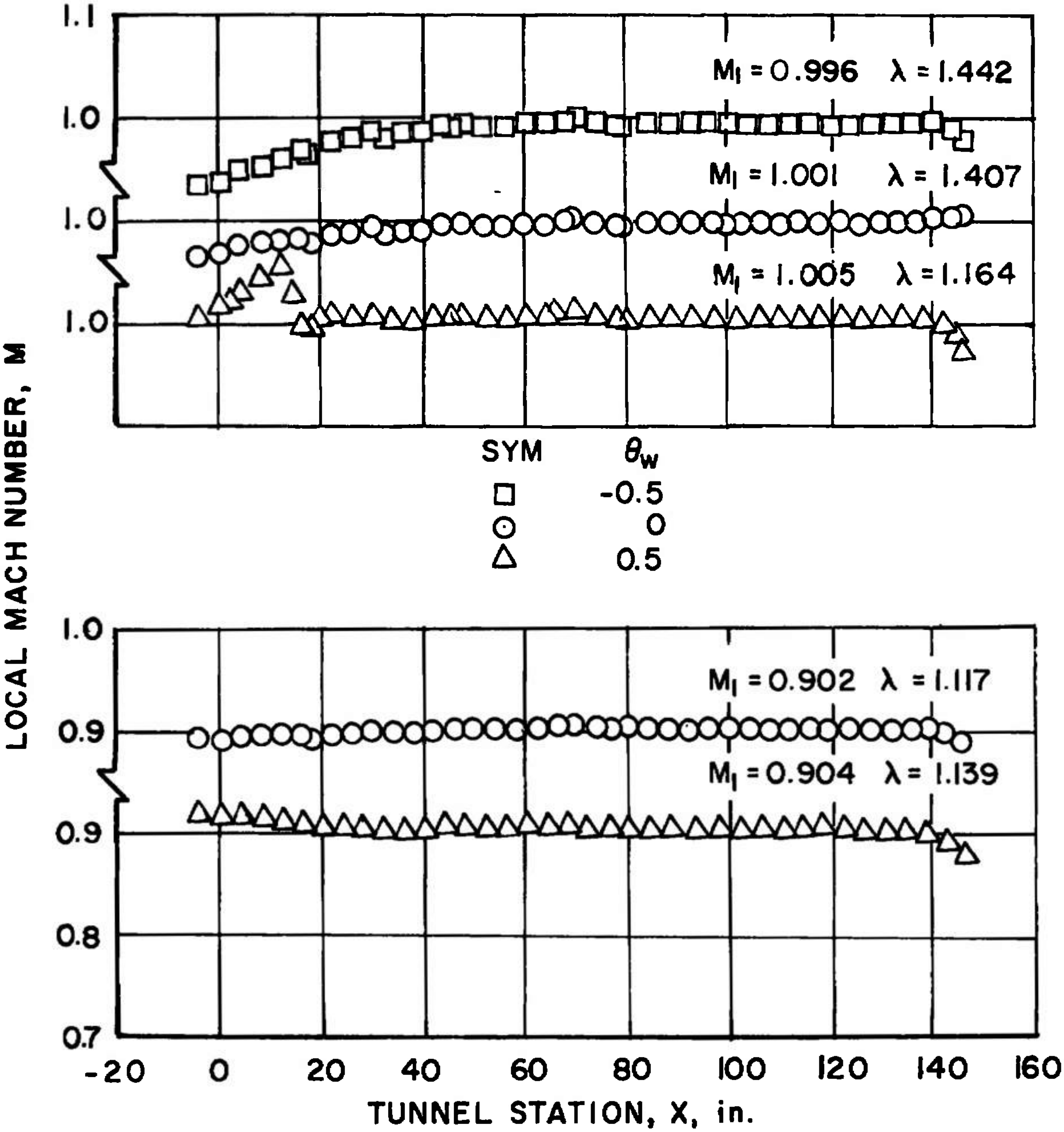


i. M = 1.30
Fig. 7 Concluded

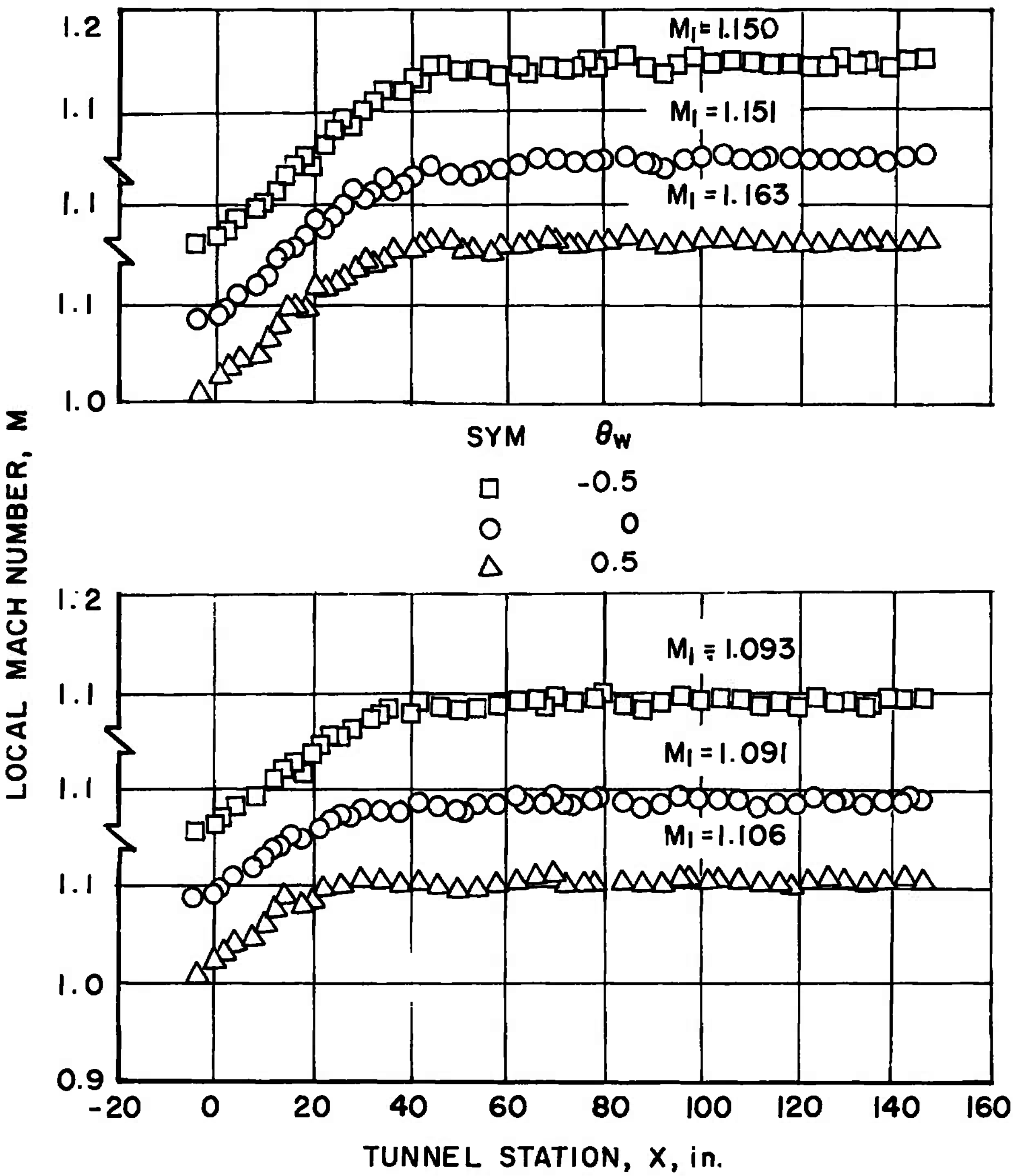


a. M = 0.60 and 0.80

Fig. 8 Influence of Wall Angle on the Centerline Mach Number Distributions, τ = 3.0



b. M = 0.90 and 1.00
Fig. 8 Continued



c. M = 1.10 and 1.15
Fig. 8 Concluded

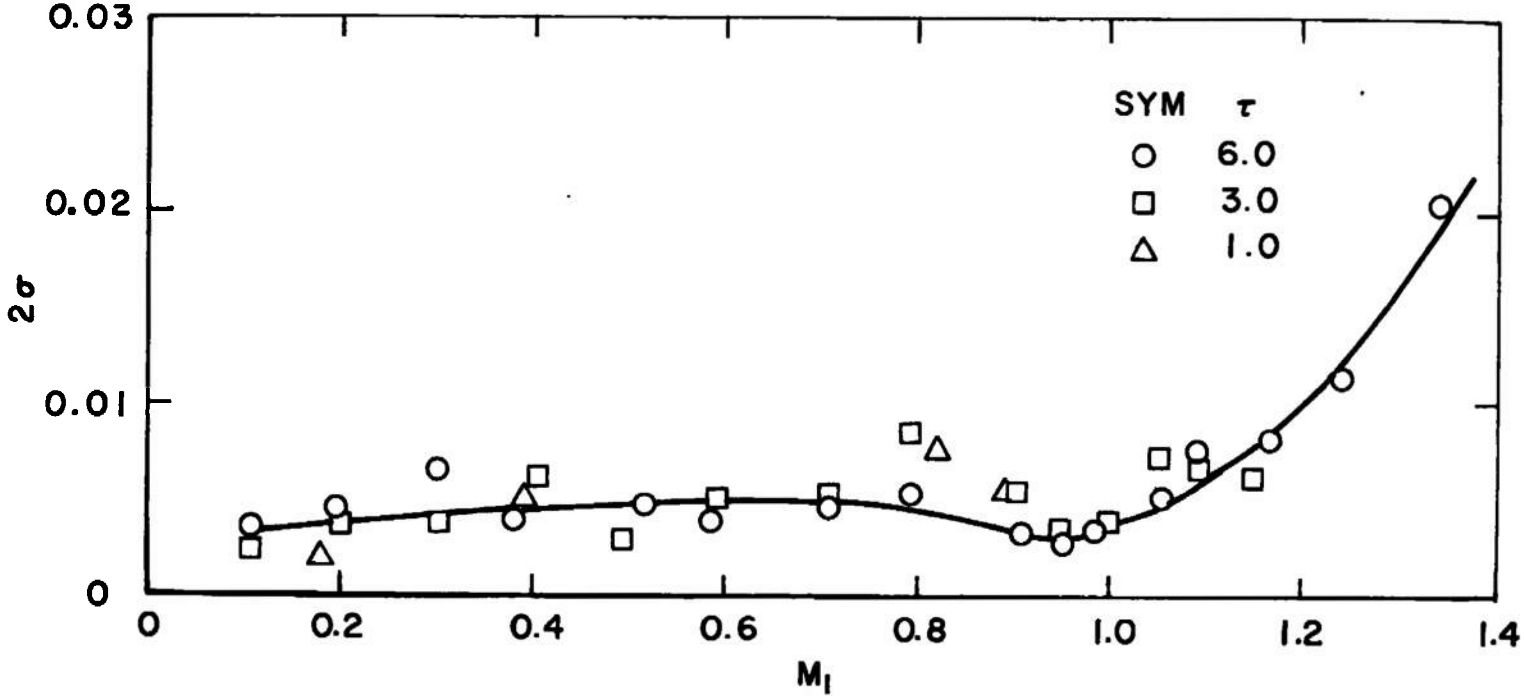


Fig. 9 Mach Number Uniformity as Expressed by the Standard Deviation Statistic, 2 σ

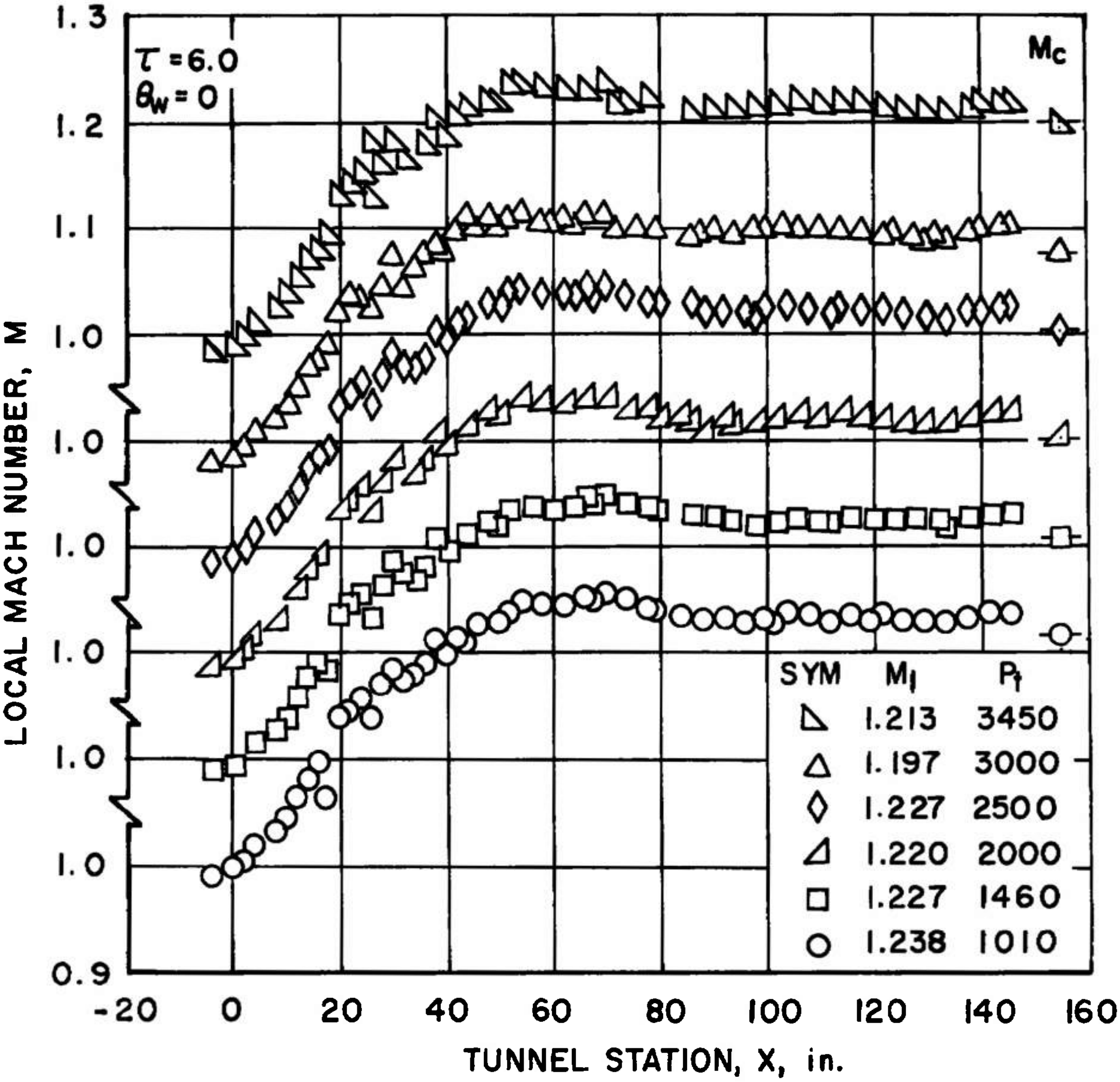


Fig. 10 Influence of Tunnel Stagnation Pressure on the Mach Number Distributions at M = 1.20, τ = 6.0, θ_w = 0

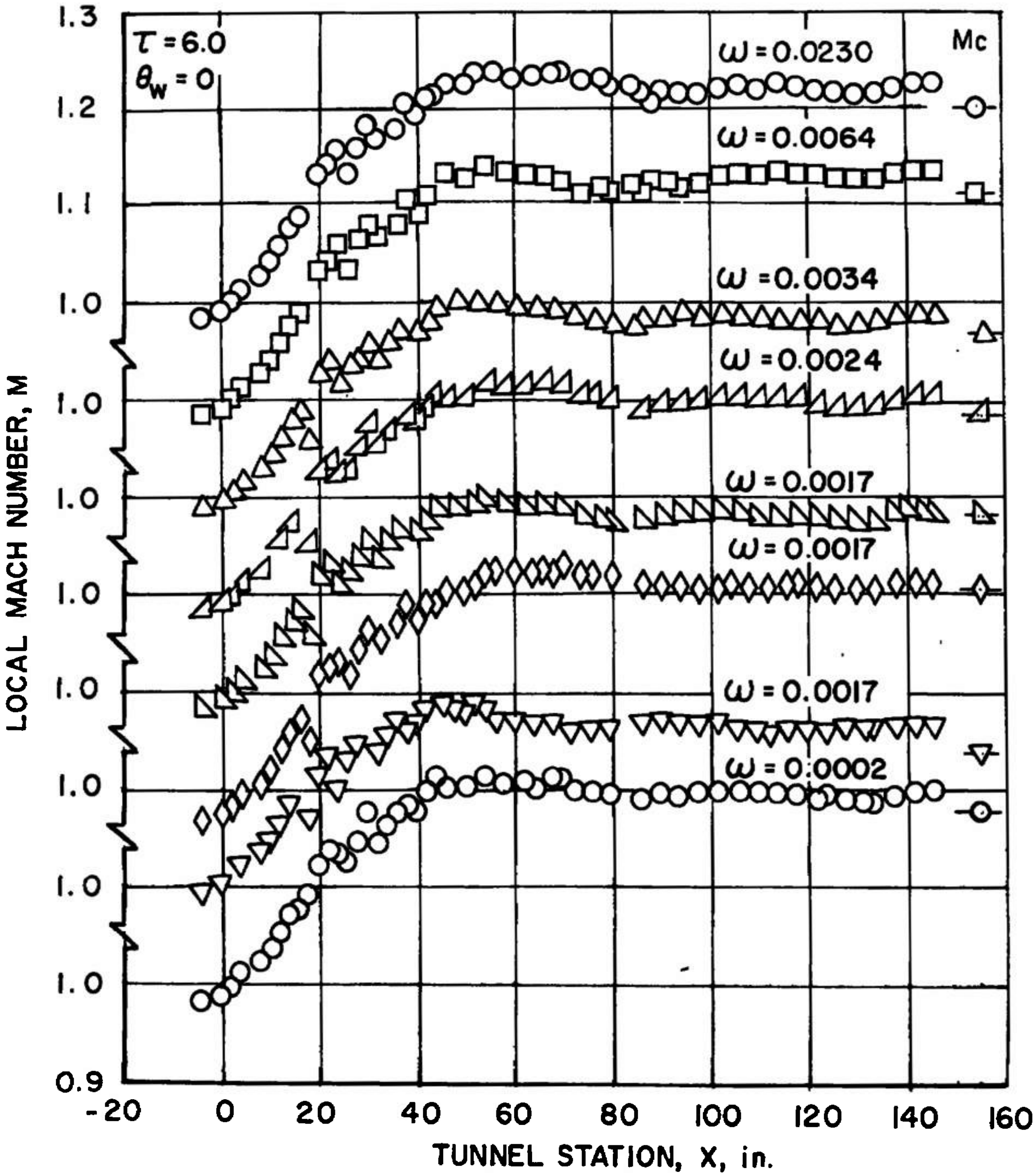
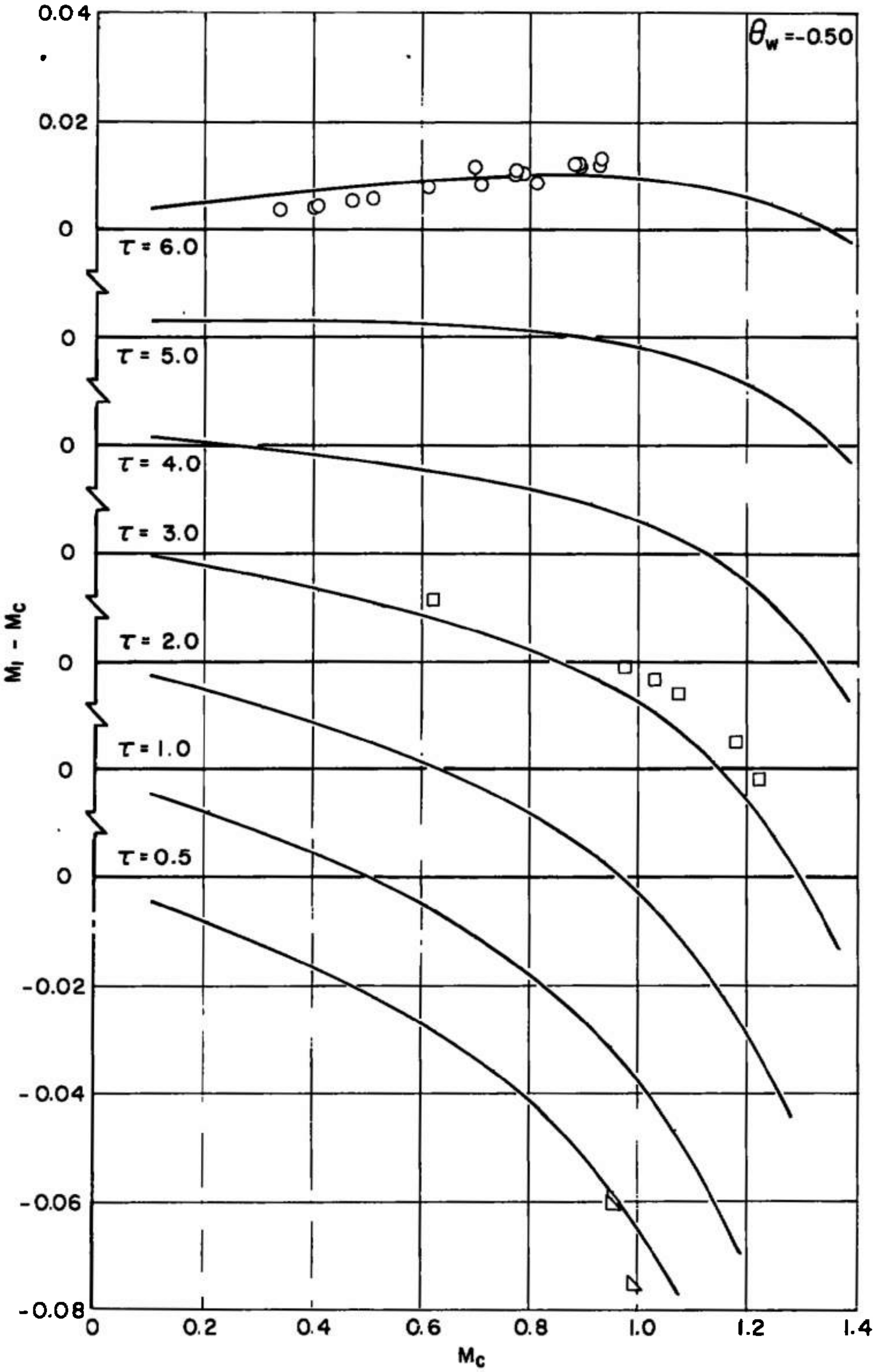
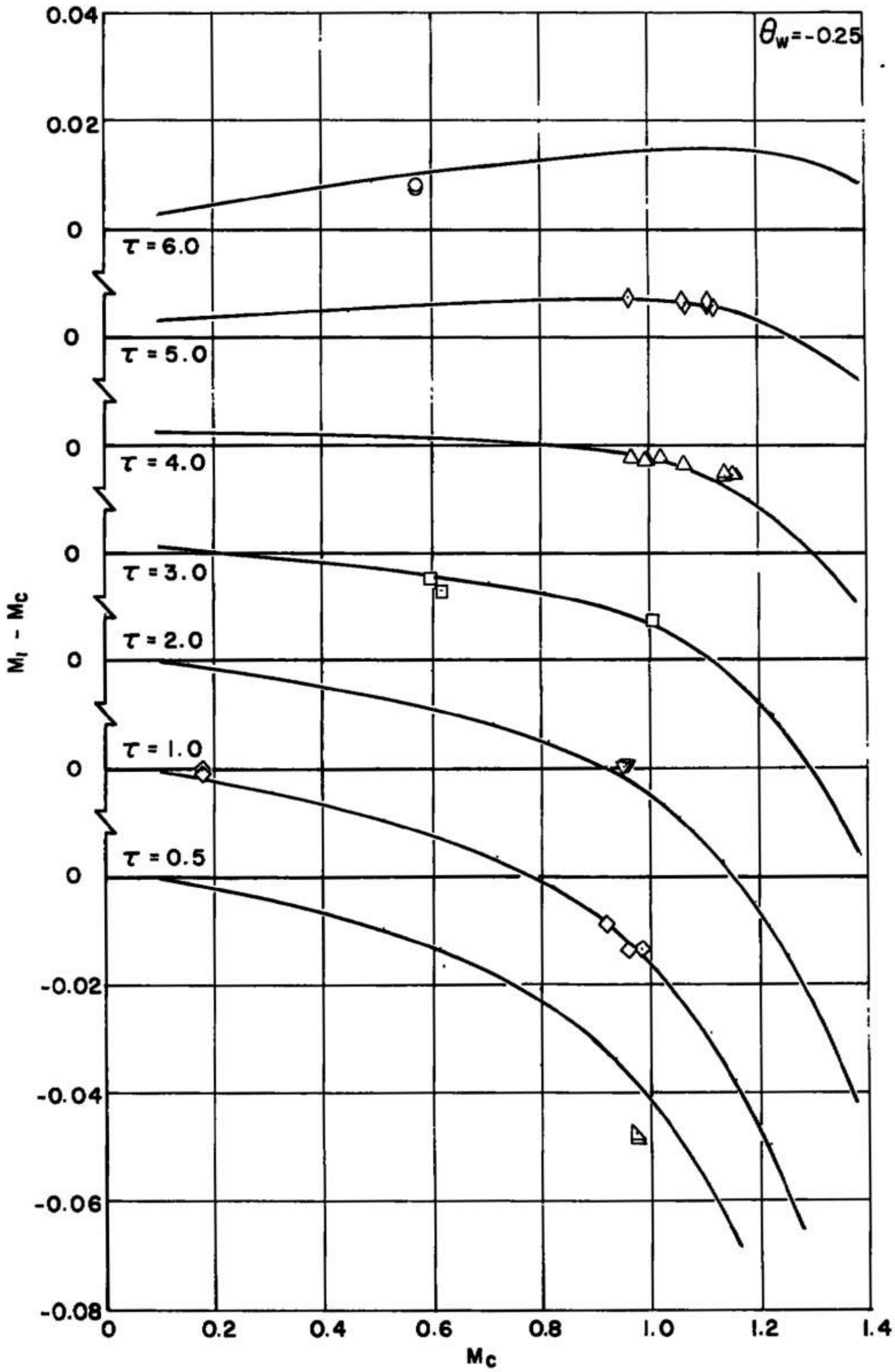


Fig. 11 Influence of Humidity on the Mach Number Distributions at M = 1.20, τ = 6.0, θ_w = 0

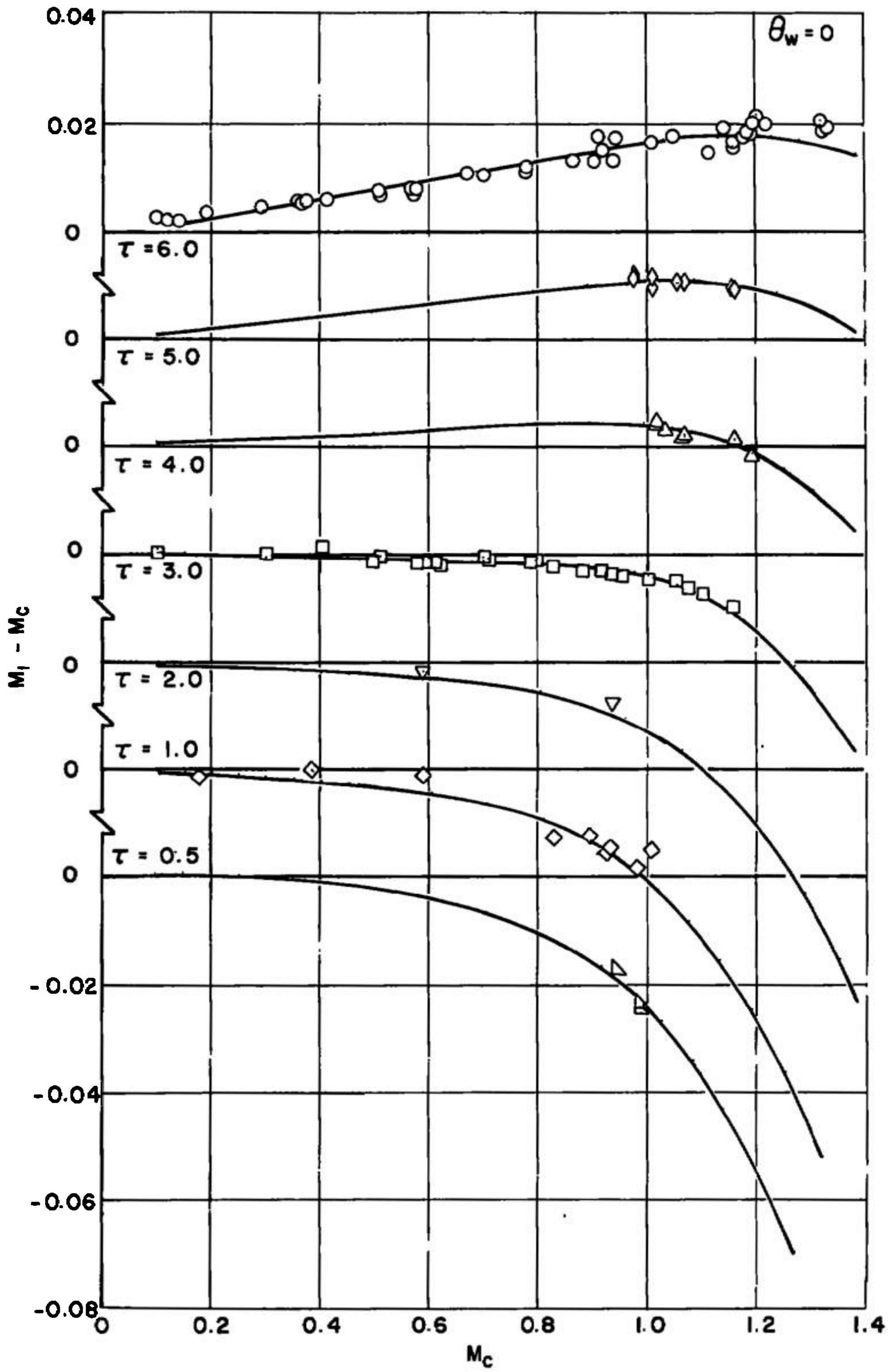


a. θ_w = -0.50

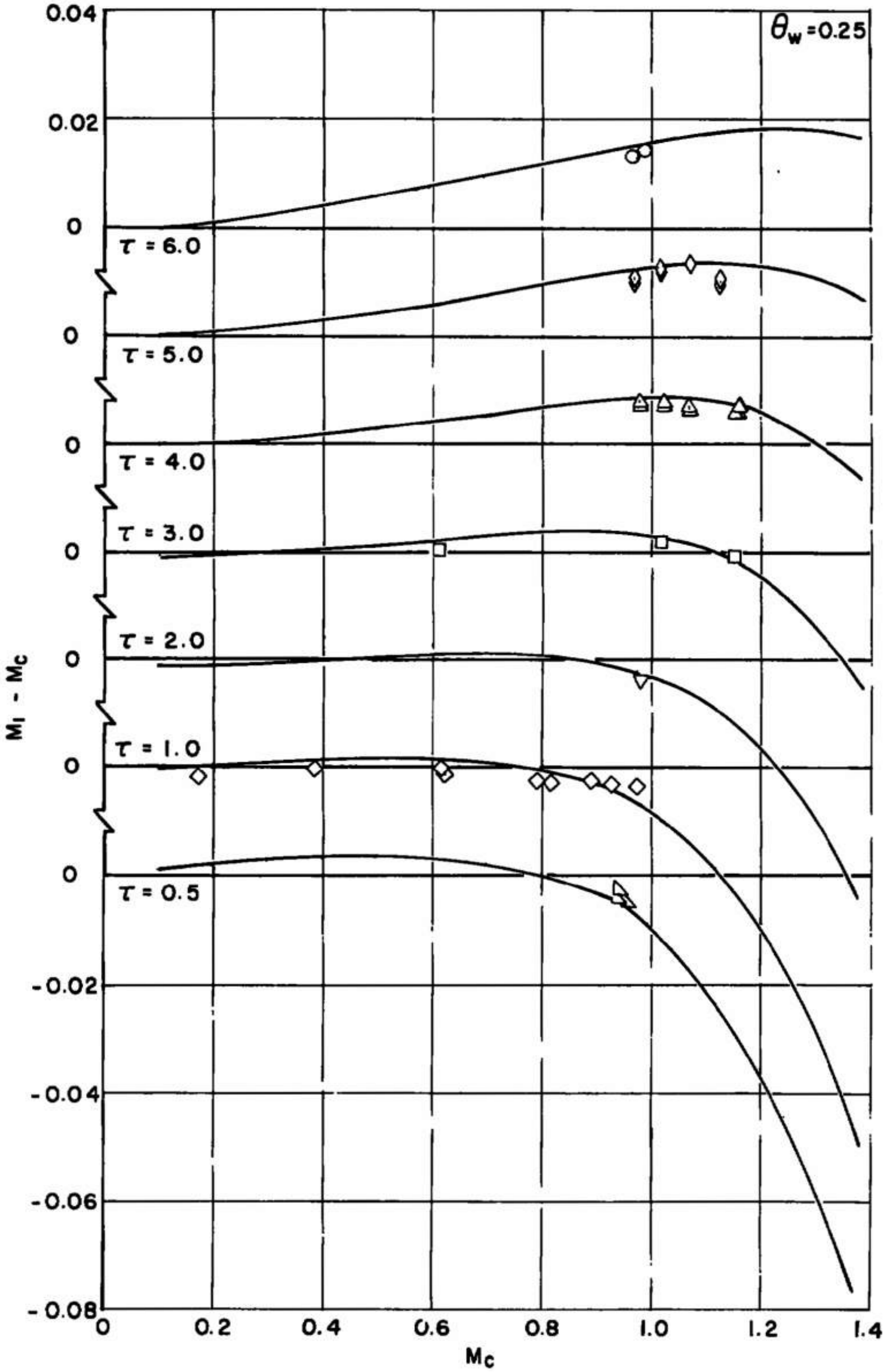
Fig. 12 Plenum-Stream Mach Number Calibration Data and Hypersurface Fit



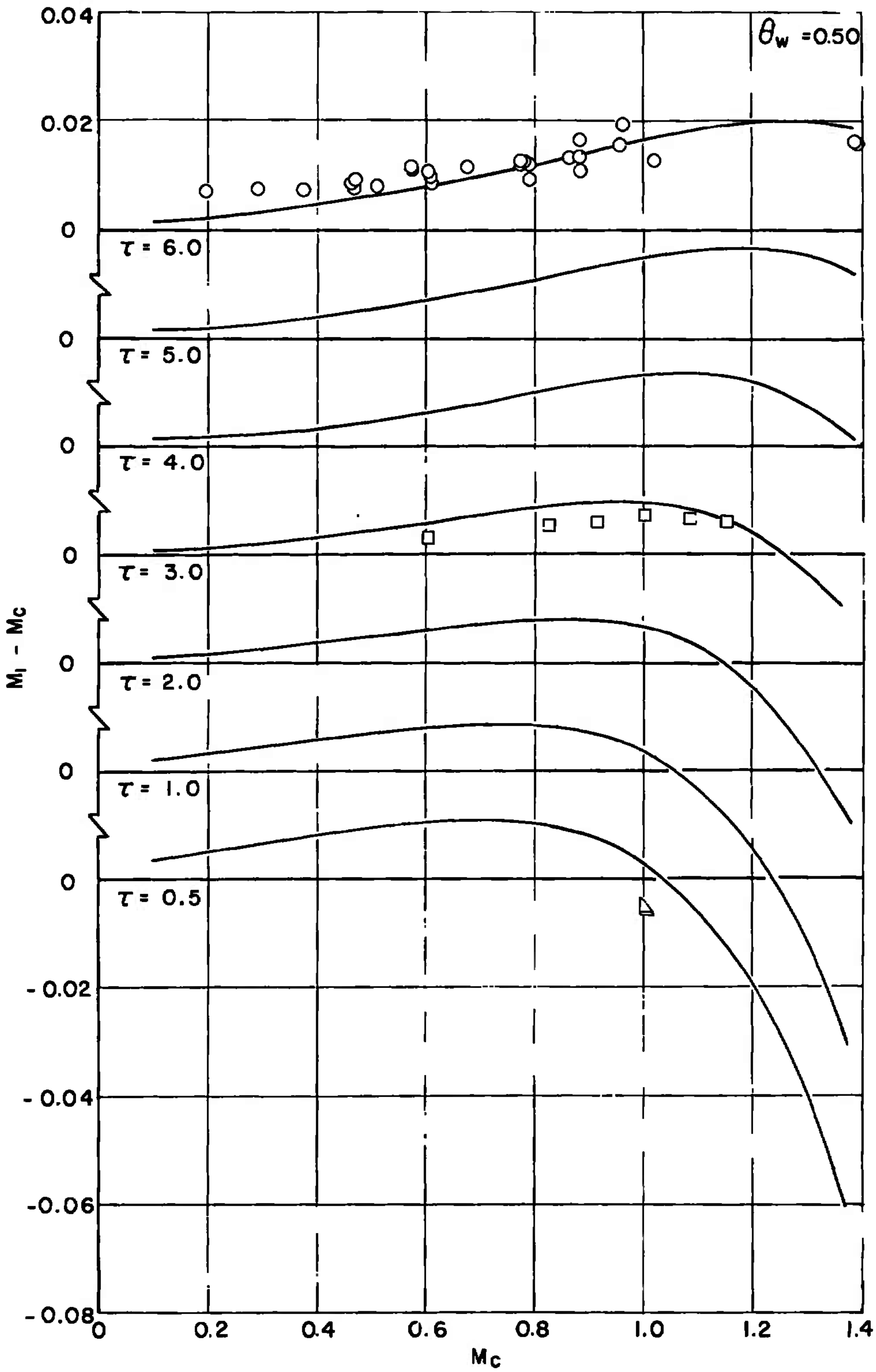
b. θ_w = -0.25
Fig. 12 Continued



c. $\theta_w = 0$
Fig. 12 Continued



d. $\theta_w = 0.25$
Fig. 12 Continued



e. θ_w = 0.50
Fig. 12 Concluded

TABLE II-1
PLENUM-STREAM CALIBRATION CONSTANTS

i	a_i	b_i
1	2.5098-02	5.3533-04
2	-3.9656-03	-1.3126-02
3	-6.9294-02	4.1810-04
4	-1.3310-02	-1.7368-03
5	2.2181-03	1.9803-02
6	6.5772-02	2.7782-03
7	1.6527-02	4.8594-02
8	2.8406-03	-2.0072-04
9	-4.3384-04	-2.8458-03
10	-3.0951-02	-4.0930-03
11	-7.9216-03	-1.0385-02
12	-1.3421-03	-1.1063-03
13	-1.8626-04	2.0356-02
14	3.4042-05	-1.1099-04
15	-1.5100-02	-1.0192-02
16	1.0738-02	-2.3558-02
17	-1.0184-03	1.3193-05
18	8.8207-05	3.2277-04
19	5.3506-06	2.2427-03
20	-8.8922-07	2.6113-02
21	9.8241-04	---

Note: 2.5098-02 = 0.025098

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13 ABSTRACT

Tests were conducted in the AEDC Aerodynamic Wind Tunnel, Transonic (4T), to determine the tunnel calibration and centerline Mach number distributions. The wall porosity in the test section is remotely variable using a sliding cutoff plate design. The walls were recently modified to allow upstream movement of these cutoff plates instead of the original downstream movement for decreasing porosity. During the tests, Mach number was varied from 0.10 to 1.35, test section wall angle from -0.5 to 0.5 deg, test section wall porosity from 0- to 10-percent open area, and stagnation pressure from 1000 to 3500 psfa. Some data were obtained showing the effects of humidity. Acceptably uniform Mach number distributions were obtained at wall porosities up to 7-percent open area, a marked improvement over the original 4T wall design. The tunnel plenum-stream calibration relationship was determined to be dependent upon Mach number, wall angle, wall porosity, and humidity but nominally independent of stagnation pressure level.

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2 Mach number						
calibrating						
test facilities						
porosity						
walls						

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